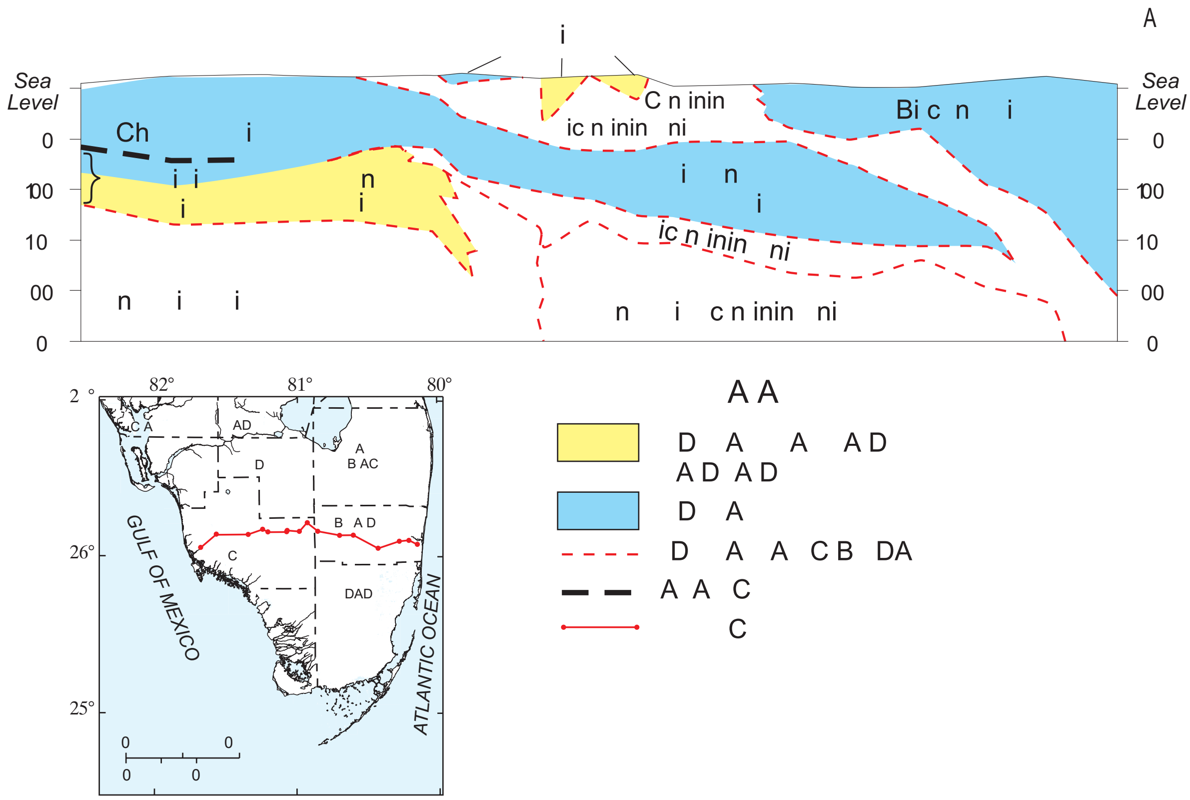
Hydrogeology of the Gray Limestone Aquifer in Southern Florida



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99-4213

Prepared in cooperation with the
SOUTH FLORIDA WATER MANAGEMENT DISTRICT

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By RONALD S. REESE and KEVIN J. CUNNINGHAM

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science for a changing world

Tallahassee, Florida
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Hydrogeology of the Gray Limestone Aquifer in Southern Florida

By Ronald S. Reese *and* Kevin J. Cunningham

Abstract

Results from 35 new test coreholes and aquifer-test, water-level, and water-quality data were combined with existing hydrogeologic data to define the extent, thickness, hydraulic properties, and degree of confinement of the gray limestone aquifer in southern Florida. This aquifer, previously known to be present only in southeastern Florida (Miami-Dade, Broward, and Palm Beach Counties) below, and to the west of, the Biscayne aquifer, extends over most of central-south Florida, including eastern and central Collier County and southern Hendry County; it is the same as the lower Tamiami aquifer to the north, and it becomes the water-table aquifer and the upper limestone part of the lower Tamiami aquifer to the west. The aquifer generally is composed of gray, shelly, lightly to moderately cemented limestone with abundant shell fragments or carbonate sand, abundant skeletal moldic porosity, and minor quartz sand.

The gray limestone aquifer comprises the Ochopee Limestone of the Tamiami Formation, and, in some areas, the uppermost permeable part of an unnamed formation principally composed of quartz sand. Underlying the unnamed formation is the Peace River Formation of the upper Hawthorn Group, the top of which is the base of the surficial aquifer system. Overlying the aquifer and providing confinement in much of the area is the Pinecrest Sand Member of the Tamiami Formation. The thickness of the aquifer is comparatively uniform, generally ranging from 30 to 100 feet. The unnamed formation part of the aquifer is up to 20 feet thick. The Ochopee Limestone accumulated in a carbonate ramp depositional system and contains a heterozoan carbonate-particle association. The principal rock types of the aquifer are pelecypod lime rudstones and floatstones and permeable quartz sands and sandstones. The pore types are mainly intergrain and separate vug (skeletal-moldic) pore spaces. The rock fabric and associated primary and secondary pore spaces combine to form a dual diffuse-carbonate and conduit flow system capable of producing high values of hydraulic conductivity.

Transmissivity values of the aquifer are commonly greater than 50,000 feet squared per day to the west of Miami-Dade and Broward Counties. Hydraulic conductivity ranges from about 200 to 12,000 feet per day and generally increases from east to west; an east-to-west shallowing of the depositional profile of the Ochopee Limestone carbonate ramp contributes to this spatial trend. The aquifer contains two areas of high transmissivity, both of which trend northwest-southeast. One area extends through southern Hendry County. The other area extends through eastern Collier County, with a transmissivity as high as 300,000 feet squared per day; in this area, the aquifer is structurally high, the top of the aquifer is close to land surface, and it is unconfined to semiconfined. The confinement of the aquifer is good to the north and east in parts of southern Hendry, Palm Beach, Collier, Broward, and Miami-Dade Counties. In these areas, the upper confining unit approaches or is greater than 50 feet thick, and vertical leakance is less than 1.0×10^{-3} 1/day.

In most of the study area, the specific conductance in water from the gray limestone aquifer is 1,500 microsiemens per centimeter or less (chloride concentration of about 250 milligrams per liter or less). Areas where specific conductance is greater than 3,000 microsiemens per centimeter are found where there is a low horizontal-head gradient and the upper confining unit is greater than 50 feet thick. An area with specific conductance less than 1,500 microsiemens per centimeter extends from southern Hendry County to the southeast into western Broward County and coincides with an area of high transmissivity. However, much of this area has good confinement. The potentiometric gradient also is to the southeast in much of the area, and this area of low specific conductance is probably caused by a relatively rapid downgradient movement of fresh ground water that has been recharged in Hendry County.

INTRODUCTION

Southern Florida is an area of rapid population growth, and expanding urbanized areas are underlain by the surficial aquifer system. Large ground-water withdrawals from the unconfined Biscayne aquifer of the surficial aquifer system in southeastern Florida could adversely affect sensitive wetlands that lie immediately west of municipal well fields and agricultural lands. These wetland areas include Everglades National Park and several large water-conservation impoundment areas that help to maintain the hydrologic regimes of southern Florida. Because of the competing municipal, agricultural, and natural ecosystem water-supply demands, alternate water supplies need to be identified and developed.

The relations between the wetland ecosystems in central-south Florida and shallow aquifers are poorly understood. A detailed understanding of the hydrogeologic framework of the surficial aquifer system and characterization of the its hydraulic properties could greatly enhance current or planned efforts to simulate the interaction between ground water and surface water. Stratigraphic and hydrogeologic correlation between the eastern and western coastal areas in the surficial aquifer system is needed.

The gray limestone aquifer of the surficial aquifer system could provide an additional water supply. Additionally, definition of the hydrogeologic framework in which it occurs and determination of its extent, depth, and hydraulic properties address the above needs and questions. The U.S. Geological Survey (USGS), in cooperation with the South Florida Water Management District (SFWMD), conducted a hydrogeologic study of the gray limestone aquifer that began in October 1995 and ended in September 1999. This study was completed in collaboration with separate USGS projects, entitled "Hydrogeology of the surficial aquifer system in southwest Florida" and “Hydrogeologic characterization and mapping of two semiconfining units in the surficial aquifer system, southeastern Florida.” The study area includes parts of Miami-Dade, Broward, Palm Beach, Monroe, Collier, and Hendry Counties (fig. 1) and lies within the U.S. Department of the Interior’s South Florida Ecosystem (Place-Based) Program study area (McPherson and others, 1995).

The gray limestone aquifer was first identified in western Broward County (Fish, 1988); subsequent drilling traced the gray limestone aquifer into western Miami-Dade County (Fish and Stewart, 1991). The aquifer was described as “composed of gray (in places, greenish-gray or tan) limestone of the lower part and locally the middle part of the Tamiami Formation” and “usually is shelly with abundant shell fragments or carbonate sand and minor quartz sand, and it is lightly to moderately cemented” (Fish, 1988). In Broward and Miami-Dade Counties, the gray limestone aquifer underlies and extends west of the Biscayne aquifer (fig. 2). It was unknown at that time if the aquifer extended westward into Monroe, Collier, and Hendry Counties, or if it was equivalent to the lower Tamiami aquifer in Hendry County (Smith and Adams, 1988) and western Collier County (Knapp and others, 1986). A shallow aquifer, referred to as the shallow aquifer of southwestern Florida, was mapped in Collier County (Klein, 1972; Klein and others, 1975); however, a map and cross section showing the extent of this aquifer indicated that it is not present in a central area near the border between Collier County and Broward and Miami-Dade Counties. In this area, only local discontinuous water-bearing material of low yield was mapped.

Most of the data for the gray limestone aquifer were collected as part of studies with a broader focus, such as those by Fish (1988) and Fish and Stewart (1991), and most hydrogeologic studies of the surficial aquifer system have been restricted to coastal areas, such as the one by Knapp and others (1986). One notable exception was a local study in central Miami-Dade County of the gray limestone aquifer, in which it was referred to as the Everglades aquifer (Labowski and others, U.S. Geological Survey, written commun., 1988).

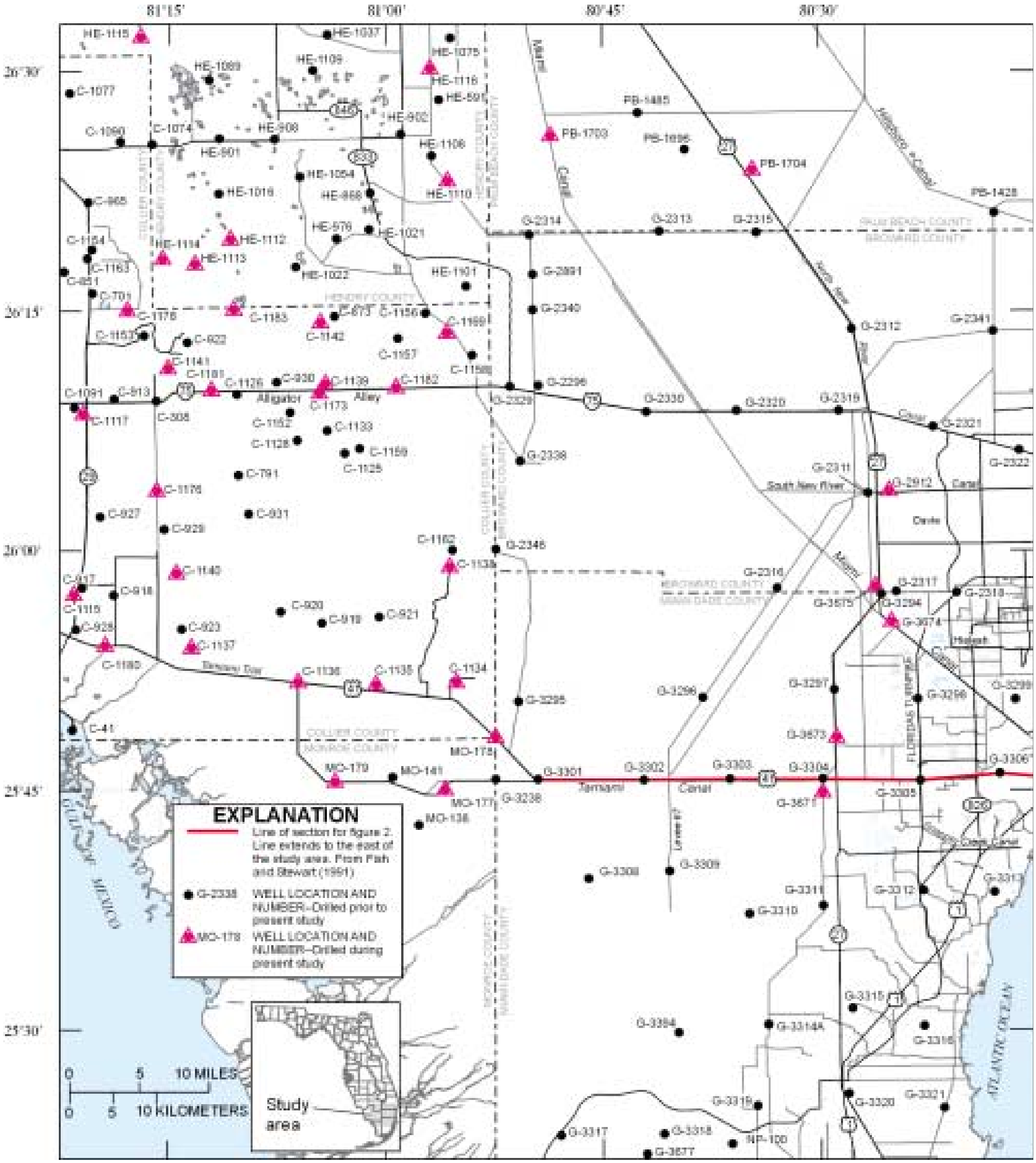


Figure 1. Location of study area and test wells used in the study. Some test well sites have more than one well. Refer to tables 1 and 2 for lists of test wells, site names, and additional wells at each site.

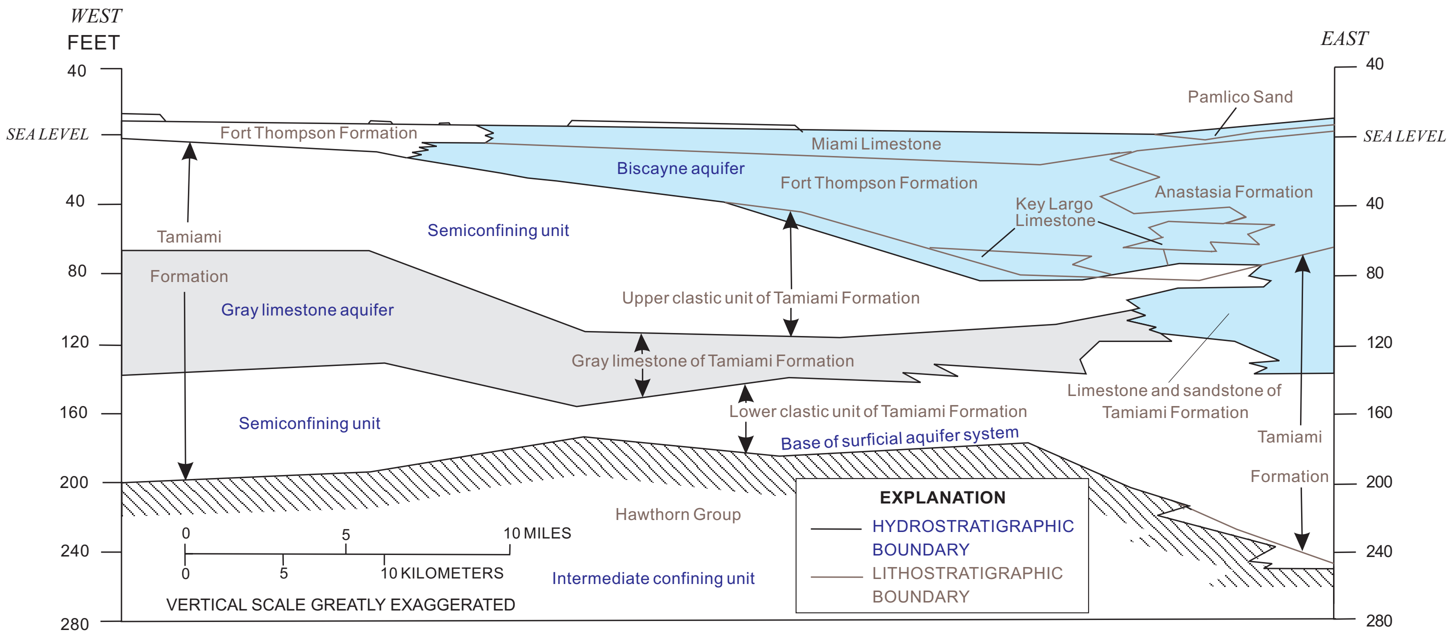


Figure 2. Hydrogeologic section in central Miami-Dade County along Tamiami Trail (modified from Fish and Stewart, 1991, fig. 6b(. Line of section shown in figure 1.

Purpose and Scope

The purpose of this report is to evaluate the hydrogeologic framework, hydraulic properties, and ground-water flow of the gray limestone aquifer in southern Florida. The report also emphasizes the geologic framework (stratigraphy and structure) and the hydrogeologic framework (aquifers and confining and semiconfining units) above and below the gray limestone aquifer. Specifically, this report: (1) delineates the configuration, thickness, and extent of the gray limestone aquifer; (2) estimates the hydraulic properties of the gray limestone aquifer (transmissivity, hydraulic conductivity, and leakance or degree of confinement) and relates these characteristics to the geologic framework; and (3) maps the distribution of water level and water quality in the aquifer.

The lithology, limiting extent, and thickness of lithostratigraphic units are determined by examination of core, well cutting samples, archived lithologic descriptions, and borehole-geophysical logs for selected wells. Four hydrogeologic sections have been constructed to show lithostratigraphic and hydrogeologic units and their structure in southern Florida, and maps have been constructed to show the configuration of the top, base, and thickness of the gray limestone aquifer. The geometry, thickness, and physical extent of the hydrogeologic units are delineated on the basis of lithologic and borehole geophysical data, well-to-well correlation, core sample analysis, evaluation of flowmeter log data, and aquifer test results. Estimates of the hydraulic properties of the gray limestone aquifer including transmissivity, hydraulic conductivity, and leakance are made by analysis of aquifer test data. Other hydraulic properties (porosity and hydraulic conductivity) of the aquifer and its bounding low permeability units are visually estimated from core samples and measured from core sample analysis. The distributions of water level and water quality in the gray limestone aquifer have been mapped to gain an understanding of ground-water flow patterns.

Relevant literature and well information contained within the files of the USGS have been compiled. Data from deep petroleum exploration and production wells supplemented the water-well data, and samples from cuttings collected from some of these wells are described. Previously collected hydraulic data pertaining to the gray limestone aquifer or to an equivalent or related aquifer have been synthesized.

Description of Study Area

The study area includes inland parts of Miami-Dade, Broward, Palm Beach, Monroe, and Collier Counties, and the southeastern part of Hendry County (fig. 1). The eastern boundary of the study area, which is in eastern Miami-Dade, Broward, and Palm Beach Counties, was chosen to include the eastern limit of the gray limestone aquifer as defined by Fish (1988) and Fish and Stewart (1991). Based on previous studies, the other boundaries were chosen such that the enclosed area could include the full extent of the gray limestone aquifer. The western part of the study area extends to central Collier County, to just west of State Highway 29. This highway nearly coincides with an axis of a thick unnamed quartz sand deposit that underlies the Tamiami Formation (Cunningham and others, 1998). The northern boundary of the study area is in central Hendry County and is just south of a surface-water divide (Parker and others, 1955, pl. 12).

Land-surface elevation in the study area ranges from sea level in coastal areas to slightly greater than 30 feet (ft) above sea level in central Hendry County and northwestern Collier County (Smith and Adams, 1988, fig. 3). Most of the study area falls into three physiographic units that include the Sandy Flatlands, Big Cypress Swamp, and the Everglades (fig. 3). The western edge of the Everglades unit adjoins the other two units, and approximately coincides with the L-2 and L-3 Canals in eastern Hendry County and the L-28 Canal in Broward and Miami-Dade Counties. The Sandy Flatlands unit in southern and central Hendry County occupies the highest part of the study area and borders the other two units typically at an elevation ranging from 15 to 20 ft above sea level (Smith and Adams, 1988, fig. 3).

The two major east to west highways that traverse the study area are Tamiami Trail (U.S. Highway 41) and Alligator Alley (Interstate 75). From west to east, major north- or northwest-trending canals include the L-28 Interceptor, L-2, L-3, L-28 (North and South), Miami, North New River, and Hillsboro Canals (fig. 3). The Tamiami Canal lies along the north side of Tamiami Trail. Water-conservation areas are present in southeastern Palm Beach County, western Broward County, and northwestern Miami-Dade County and occupy much of the Everglades unit area (fig. 3). Water flows, or is back-pumped, into these water-conservation areas and is stored to: (1) maintain ground-water levels, (2) provide recharge to municipal well fields, and (3) maintain surface-water flows to Everglades National Park.

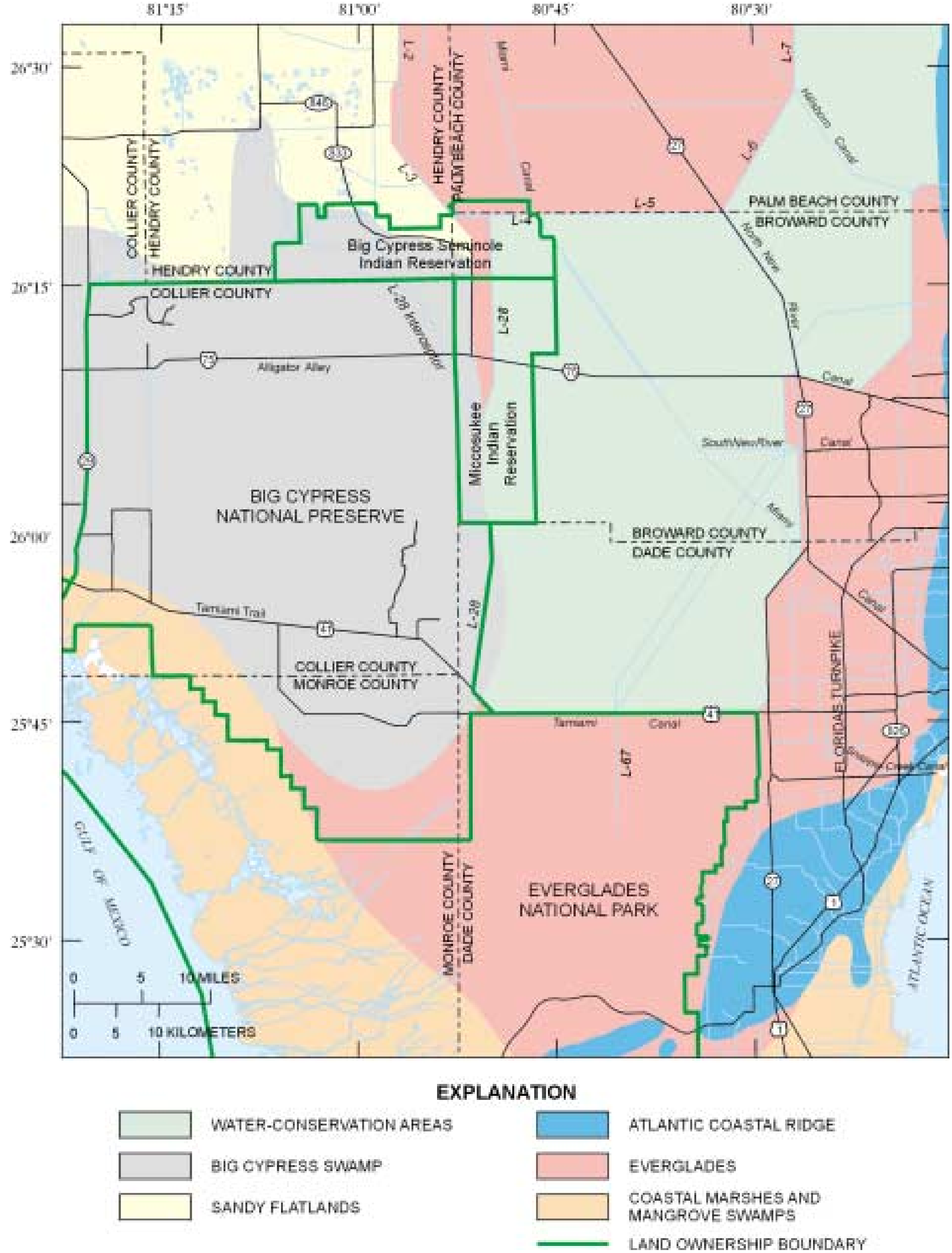


Figure 3. Physiographic units, water-conservation areas, and Indian Reservation Lands in the study area. Modified from Parker and others (1955, pl.12).

Important public land areas in the study area include Big Cypress National Preserve and Everglades National Park (fig. 3). Two other important land ownership areas are the Miccosukee Indian Reservation in western Broward County, and the Big Cypress Seminole Indian Reservation in southeastern Hendry County and extreme northwestern Broward County.

Previous Studies

Several "classic" early studies contributed to the geology and hydrogeology of the surficial aquifer system in southern Florida, such as Parker and others (1955), DuBar (1958), McCoy (1962), and Klein and others (1964). The base of the surficial aquifer system in Big Cypress Preserve and Everglades National Park was mapped by Jarosewich and Wagner (1985). Since the late 1980's, the SFWMD has completed two reconnaissance hydrogeologic studies (Knapp and others, 1986; Smith and Adams, 1988) and has constructed two ground-water flow models (Smith, 1990; Bennett, 1992) of the surficial aquifer system and the upper part of the intermediate aquifer system in the extreme western and northwestern parts of the study area (western Collier County and Hendry County). Reports by Causaras (1985; 1987), Fish (1988), and Fish and Stewart (1991) combine to define a hydrogeologic framework of the surficial aquifer system in Broward and Miami-Dade County, respectively. For Palm Beach County, Miller (1987) prepared lithostratigraphic sections that include the formations composing the surficial aquifer system; however, the extent of these formations was not delineated. Weedman and others (1997) and Edwards and others (1998) presented multidisciplinary geologic studies of the surficial aquifer system in western Collier County. Prior to the current study, the subsurface hydrogeology of the surficial aquifer system in eastern Collier County remained virtually unstudied; however in a concurrent study, Weedman and others (1999) describe the lithostratigraphy and geophysics of the surficial aquifer system in eastern Collier County and the most northeastern part of peninsular Monroe County.

Acknowledgments

Contributions and technical assistance were made by numerous individuals and governmental agencies. Especially important was a constructive, collaborative effort with Suzanne Weedman (USGS). Fred Paillet (USGS) collected and interpreted borehole geophysical log data on most of the test coreholes. Don Weeks, hydrologist with the Big Cypress National Preserve, assisted with site selection and obtaining permission to drill wells and conduct aquifer tests. Christine Bates, Pat Kinney, and Ron Clark (also with the Big Cypress National Preserve) were very helpful. Jim Trindell of the Florida Geological Survey (FGS) drilled 13 test coreholes and 3 monitoring wells and installed monitoring wells in all of the test coreholes. Jim proved to be reliable and knowledgeable in this effort. The FGS core drilling program was supervised by Tom Scott. Four production wells and 22 monitoring wells were drilled by Tony Lubrano (SFWMD), who also provided valuable advice about equipment procurement and setup for aquifer tests. Peter Dauenhauer and David Demonstranti (SFWMD) provided borehole geophysical logs for several test holes. Aquifer-test and water-level data were provided by Gail Murray (Murray Consultants, Inc., 1989) for the Big Cypress Seminole and Miccosukee Indian Reservations. Frank Rupert (FGS) provided assistance with some paleontologic identifications.

A number of people in the USGS office in Miami, Fla., contributed to this project. Steven Memberg and David Schmerge provided valuable assistance both in the office and the field. Bob Mooney also played an important role, providing logistical support, site selection, land-owner negotiations, and permitting. During the first half of the project, Scott Prinos assisted in the field and described cores. Other personnel who assisted in the field were Richard Verdi, Rich Krulikas, Loretta Leist, Anne Vlad, and Tony Brown.

METHODS OF INVESTIGATION

Intensive field and laboratory work was performed during this study. This work principally included well drilling, coring, and construction; borehole geophysical logging; core description and analysis in the laboratory; aquifer testing; and data collection from completed wells. The data collection from completed wells included some additional borehole geophysical logging, water-level measurements, and water-quality sampling and analysis.

Well Drilling, Coring, and Inventory of Wells

Test wells drilled at 35 sites during this study (fig. 1 and table 1) form the foundation of the physical framework described herein. Three test wells are located in northeastern Monroe County, 19 in eastern

Table 1. List of wells drilled during the study

[Well C-995 was the only well drilled prior to this study. All test wells were continuously cored, except for wells C-1173 and HE-1110, which were drilled by the dual-tube, reverse-air method. Borehole geophysical logging suite for test well: Basic represents induction resistivity, natural gamma ray, spontaneous potential, and single-point resistance logs; complete represents all logs listed for basic as well as neutron porosity, fluid resistivity, fluid temperature, and heat-pulse flowmeter logs. USGS, U.S. Geological Survey]

Test well (USGS local well number shown in fig. 1)	Site name	Borehole geophysical logging suite for test well	Additional wells at site (USGS local well number not shown in fig. 1)
C-1115	Fakahatchee Ranger Station	Complete	C-995
C-1117	Fakahatchee Jones Grade	Complete	
C-1134	Dade-Collier Airport	Complete	C-1148, C-1149
C-1135	FAA Radar	Complete	C-1143, C-1144 to C-1147, C-1172
C-1136	Monroe Station	Complete	C-1150
C-1137	Doerr’s Lake	Complete	
C-1138	Raccoon Point	Complete	
C-1139	Noble’s Road	Complete	C-1184, C-1185
C-1140	Bass	Complete	
C-1141	Bear Island Campground	Complete	C-1165, C-1166, C-1167
C-1142	Noble’s Farm	Basic	
C-1169	Big Cypress Sanctuary	Complete	C-1170, C-1171
C-1173	Sabine Road	Basic	C-1174
C-1176	Turner River Road	Complete	C-1177
C-1178	Sunniland II	Complete	C-1179
C-1180	Big Cypress Headquarters	Complete	
C-1181	Cypress Lane	Complete	
C-1182	Alligator Alley East	Basic	
C-1183	Baker’s Grade	Basic	
G-2912	South New River Canal, B-5	Basic	
G-3671	West Bird Drive Basin, B-1	Basic	
G-3673	Levee 31, B-2B	Basic	
G-3674	Miami Canal, B-3	Basic	
G-3675	Snake Creek Canal, B-4	Basic	
HE-1110	L-3 Canal	Basic	HE-1111
HE-1112	Windmill Road	Basic	
HE-1113	Prison I	Basic	
HE-1114	Prison II	Basic	
HE-1115	Mustang Grade	Basic	
HE-1116	L-2 Canal	Basic	HE-1117
MO-177	Golightly	Complete	MO-184
MO-178	Trail Center	Complete	MO-180 to MO-183, MO-185 to MO-188
MO-179	West Loop Road	Complete	
PB-1703	G-200 Pump Station	Basic	
PB-1704	Sod Farm	Basic	

Collier County, 6 in Hendry County, 2 in southwestern Palm Beach County, 1 in Broward County, and 4 in Miami-Dade County. A total of 33 test wells were continuously cored, and 2 were drilled by the dual-tube reverse-air rotary method. Most of the test wells were drilled to a depth of about 200 ft below land surface. Fourteen of the test wells were drilled as part of this study, 16 were drilled under the direction of separate studies (Weedman and others, 1997; Edwards and others, 1998; and Weedman and others, 1999), and 5 were drilled as part of a concurrent study on the effectiveness of local semiconfining units contained within the Biscayne aquifer in Miami-Dade and Broward Counties (K.J. Cunningham, U.S. Geological Survey, written commun., 1998). In addition to the 35 test wells, 30 wells were drilled (as part of this study) at the test well sites as monitoring or production wells. These wells are given in table 1, where they are listed under additional wells at a site. Large areas in the Big Cypress Swamp and the Everglades, such as between Alligator Alley and Tamiami Trail in eastern Collier County, could not be evaluated because of inaccessibility. An exception was well C-1138 at the Raccoon Point site located at the terminus of a road that extends 11 mi (miles) north of Tamiami Trail (fig. 1).

Continuous core drilling was preferred to the conventional rotary method in which cutting samples are obtained. The availability of core samples enhanced the opportunity to estimate porosity and permeability of rock and sediment, determine probable environments of deposition, and obtain better control on the depth to specific geologic and hydrogeologic units. Coreholes were drilled by using a Mobile B-61 drill rig (USGS) and a Failing 1500 drill rig (FGS). Both drill rigs utilized wireline coring methods. The two semi-continuous test coreholes were drilled by the SFWMD using the dual-tube, reverse-air method. Monitoring wells also were drilled by the dual-tube method. In the dual-tube method, drilling mud is not used, and uncontaminated rock and formation water samples are collected every 5 ft as drilling progresses. One advantage to this drilling technique is that it provides a qualitative measure of the formation "productivity" as the well is being drilled because water flowing into the borehole from productive intervals is forced up the inside of the drill pipe by compressed air injected near the bottom of the drill string.

Data from 163 wells drilled prior to this study also were used, with most of these wells used to assist in mapping hydrogeologic boundaries. The locations of historical test wells are shown in figure 1, but additional wells used in this study located at the same site as a test well are not shown, rather they are listed in table 2. Identification, location, and construction data for all wells used in this report are presented in appendix I. This information and other details are stored in the USGS Ground-Water Site Inventory (GWSI) database.

Borehole Geophysical Logging

For most test wells drilled during this study, borehole geophysical logs were run including induction resistivity, natural gamma ray, spontaneous potential, and single-point resistance. Induction resistivity was determined by using an electromagnetic induction tool that measures formation conductivity. In most cases, borehole geophysical tools were run in holes containing drilling mud and with polyvinyl chloride (PVC) or steel surface casing set to a depth ranging from 10 to 40 ft. In some instances tools were not run until after the well was completed with PVC casing; under these conditions only induction resistivity and gamma-ray measurements are useful. Borehole geophysical measurements were useful in determining the depth interval to screen in a well, defining geologic and hydrogeologic boundaries, determining relative changes in formation water quality, and correlating stratigraphy from well to well.

A more complete suite of borehole geophysical logs was run for 18 of the test coreholes (table 1). The additional logs included neutron porosity, fluid resistivity, fluid temperature, and heat-pulse flowmeter logs. Tools were run in a 3-in. (inch) diameter continuously slotted PVC screen, temporarily installed in the test hole after coring. A flushing and development process removed most drilling mud and caused unconsolidated formation to collapse and fill the annulus around the screen. However, based on flowmeter log results, collapse of the formation around the screen in some wells was not complete. For the wells in which a more complete suite of logs was run, a discussion of procedures used, description of logging tools used by type, and plots of log traces collected for each well are provided in Weedman and others (1997; 1999).

Table 2. List of historical wells used in the study with more than one well used at a site

[Other historical test wells used for the study and shown on figure 1 are given in appendix I. SFWMD, South Florida Water Management District sites]

Test well (USGS local well number - shown in fig. 1)	Site name or other well identifier	Additional wells at site (USGS local well number - not shown in fig. 1)
C-965	C-2042 (SFWMD)	C-966
C-1074	C-2066 (SFWMD)	C-131
C-1077	C-2064 (SFWMD)	C-1075, C-1076
C-1163	U of M Sunniland I	C-1164
G-2296	S-140 Pumping Station, BOF-1	G-2907, G-2908
G-3294	Opa-Locka West Airport, DAT-003	G-3294C
G-3295	Levee 28, DAT-004	G-3295A, G-3295C
G-3296	Levee 67, DAT-005	G-3296A, G-3296C
G-3301	Forty-Mile Bend, DAT-010	G-3301C
G-3302	Tamiami West, DAT-011	G-3302A, G-3302C
G-3303	Tamiami Central, DAT-012	G-3303A, G-3303C
G-3304	Tamiami East, DAT-013	G-3304C
G-3305	Florida International University, DAT-014	G-3305C
G-3308	Shark Valley Tower, DAT-017	G-3308C
G-3309	Levee 67 Extension, DAT-026	G-3309A, G-3309C
G-3310	Chekika Hammock State Park, DAT-018	G-3310A, G-3310C
G-3311	Levee 31N, DAT-019	G-3311A, G-3311D
G-3314A	Homestead Airport, DAT-023	G-3314C
G-3317	Sisal Pond, DAT-027	G-3317C, G-3317D
G-3318	Park Research Center, DAT-028	G-3318A, G-3318C
G-3394	Context Road West, DAT-022	G-3394B
HE-1016	Barron Collier, HY 314	HE-1042
HE-1022	Seminole Tribe site 1, HY 311	HE-1062, HE-1063
HE-1037	ALICO site C, HY 207	HE-1036

For comparative purposes, the heat-pulse flowmeter was run in boreholes under ambient, and either injection or pumped conditions. Flowmeter data pairs for each well were analyzed to determine the transmissivity of water-producing zones as a fraction of the transmissivity of the entire borehole. Flowmeter profiles showing the relative transmissivity of 10-ft zones in eight test holes in the study area were then plotted (Weedman and others, 1999).

Borehole geophysical tools also were run in monitoring and production wells at sites where multiwell aquifer tests were conducted. The suite of borehole logs collected in some of the monitoring and production wells at these sites included gamma ray, induction resistivity, and heat-pulse flowmeter; in addition to these logs types, fluid column resistivity and temperature logs were collected in the production wells.

Core Description and Core Sample Analysis

Core samples were macroscopically described in the laboratory by using a 10-power hand lens to determine vertical patterns of microfacies, sedimentary structures, lithostratigraphic boundaries, and depositional sequence boundaries, and to assess the regional-scale rock unit variability. The rock colors of dry samples were recorded by comparison to a rock-color chart with Munsell color chips (Geological Society of America, 1991). Hydraulic conductivity of cores were visually estimated using a classification scheme based on local lithologies and physical properties of sediments developed by Fish (1988, table 8) and also used by Fish and Stewart (1991). This scheme distinguishes five categories of hydraulic conductivity within the surficial aquifer system in Broward and Miami-Dade Counties and allows comparison of the hydraulic conductivities to lithology, grain size, clay content, and solution features:

Category	Hydraulic conductivity range (feet per day)
Very high	Greater than 1,000
High	100 to 1,000
Moderate	10 to 100
Low	0.1 to 10
Very low to practically impermeable	Less than 0.1

Core sample descriptions are provided in appendix II for all but seven test wells listed in table 1. Descriptions for core samples from two of these wells (C-1115 and C-1117) are given by Weedman and others (1997); and descriptions for core samples from the remaining five wells (G-2912, G-3671, G-3673, G-3674, and G-3675) will be provided in a later USGS publication. Additionally, as part of this study, cuttings from samples collected from 10 historical test wells were described (C-1133, C-1152, C-1154, C-1156, C-1157, C-1158, C-1162, HE-1089, MO-138, and PB-1696). These descriptions are not included in appendix II, but are available in USGS files.

Forty thin sections of core samples were examined by using standard transmitted-light petrography to characterize and interpret rock and hydraulic properties (appendix III). Porosity, horizontal permeability to air, and grain density of 32 limestone and sandstone core-plug samples were quantified by analysis at Core Laboratories, Inc. All continuous cores collected or used in this study are archived at the FGS in Tallahassee, Fla.

Aquifer Testing

Aquifer tests were performed at 6 sites; a total of 10 tests were conducted, including 4 multiwell tests and 6 single-well tests. The multiwell-test production wells were constructed with 6- or 8-in. PVC casing and screen. The screen was the continuous-slotted type with a slot size of 20 or 40 and was gravel packed. Monitoring wells constructed with 2-in. PVC casing and sand-packed screen (continuous-slotted type, with slot size of 20) were used for the single-well tests.

Average single-well test pumping rates ranged from 17 to 98 gal/min (gallons per minute), depending on the depth, length of screened interval, and the transmissivity of the aquifer. The duration of pumping was about 1 to 3 hours, followed by a recovery period of 1 to 2 hours. The pumping rate was continuously monitored using an in-line vortex flowmeter.

A 4- or 6-in. suction-lift pump with a check valve was used in the production wells for the multiwell tests. Discharge was measured by using a 6-in. orifice pipe located at the end of the discharge hose by continuously recording pressure in the orifice pipe with a pressure transducer. As a check, discharge rates were monitored by using an in-line-impeller flowmeter. Average discharge rates during these tests varied from about 170 to 300 gal/min. Although 24-hour pumping periods were planned, the duration of pumping ranged from 5 to

24 hours because of problems with keeping the pump running. The number of monitoring wells for each test ranged from two to seven, and the production well and all of the monitoring wells were instrumented with pressure transducers.

Background water levels in monitoring wells were measured for a period of several days to greater than a month prior to the multiwell aquifer tests. For a selected day, the background water level for the same period of day as the pumping period was subtracted from the water-level data collected during the test. A number of difficulties occurred during the multiwell tests including lower-than-expected pumping rates, limited drawdown in monitoring wells, a rapid decline in baseline water levels, and mechanical problems associated with the pump.

Water-Level Data Collection

Water-level data were collected to help define the hydraulic properties of the aquifer, provide background data prior to aquifer tests, and construct a synoptic water-level map. Down-hole pressure transducer/data logger units were used to collect continuous water-level measurements, with a data-collection interval of 5 or 10 minutes. For synoptic data collection, the same transducer units were used, but at most wells either a steel tape or an electric water-level tape was used. Steel tape and electric water-level tape measurements were found to agree with each other within 0.01 ft. Water levels for most of the wells in Hendry County were measured by the SFWMD. To supplement data collected by the USGS and SFWMD, some measurements were selected from chart recordings made by the Seminole Big Cypress Indian Reservation.

A synoptic map was prepared using water-level data collected in 69 wells located at 47 separate sites. Water levels of both the water-table aquifer and the underlying gray limestone aquifer were collected at sites with dual completions. Additionally, at some sites concurrent canal surface-water levels were recorded. Altitude datum at each site was determined by using conventional leveling or differential global positioning surveying (GPS), and all altitudes were referenced to the North American Vertical Datum of 1988. The GPS-determined datums were required at 21 sites due to their remoteness and lack of nearby benchmarks. In the more remote areas, GPS-determined datums required a network consisting of benchmarks, temporary benchmarks, and unknowns, whereby unknowns were determined from more than one baseline and the error was distributed. First-order or second-order benchmarks were used, and the accuracy of datum determination using GPS was estimated to range from 0.1 to 0.16 ft.

Water-Quality Data Collection

Monitoring and production wells were routinely sampled shortly after they were completed, and 24 wells were sampled during an 8-day period in late August to early September 1998. Field analysis procedures followed are given by Wilde and Radtke (1998). Specific conductance and chloride concentration were measured during the routine sampling. If drilling mud was used to drill a well, this mud and fine sediment were cleaned out of the well by using a long suction hose connected to a suction-lift pump; the hose was repeatedly lowered to the bottom of the well during pumping. Specific conductance was measured in the field and laboratory, and chloride concentration was determined in the laboratory.

Major ion and low-level nutrient analyses were performed on the water samples collected from the 24 wells sampled during the 8-day period. Color, dissolved-solids concentration, field pH, specific conductance, and total alkalinity also were determined. Low-level nutrient analyses included total sample analysis of all phosphorous and nitrogen species. These 24 wells included 18 wells completed in the gray limestone aquifer and 6 wells completed in a deeper aquifer. After purging wells with a suction-lift pump, samples were collected by using a peristaltic pump that pumped through silicon tubing placed down the well. All data have been archived in the USGS water-quality data storage and retrieval database (QWDATA).

GEOLOGIC FRAMEWORK OF SOUTHERN FLORIDA

Limestones, sandstone, quartz and carbonate sand, and clay compose most of the shallow rock and sediment that are the focus of this study in southern Florida. The emphasis of the stratigraphic study herein is on the rock and sediment contained within the gray limestone aquifer, and those above and below the gray limestone aquifer that include confining or semiconfining units. Discussion of the structure is based mostly on two maps that were constructed to show the altitude of the top and base of the gray limestone aquifer.

Stratigraphy

Lithostratigraphic units of primary interest in this study are those contained within the gray limestone aquifer and those affecting the upper and lower boundary conditions of the aquifer (fig. 4). They include the Peace River Formation of the upper Hawthorn Group, an unnamed formation, the Tamiami Formation (Ochopee Limestone and Pinecrest Sand Members), and rock and sediment of Quaternary age. Rock and sediment of Quaternary age include the Key Largo Limestone, Anastasia Formation, Fort Thompson Formation, Miami Limestone, Pamlico Sand, and Lake Flirt Marl. These Quaternary units occur locally in the study area (Parker and Cooke, 1944; DuBar, 1958; McCoy, 1962; Klein and others, 1964; and Causaras, 1985; 1987); however, they were not observed or differentiated in most new test coreholes nor reported in archived well data available for Hendry, Palm Beach, Collier and Monroe Counties. Causaras (1985; 1987) shows the distribution or the absence of these units in a series of sections that extend across Broward and Miami-Dade Counties.

The lithology, limiting extent, and thickness of lithostratigraphic units were determined by examination of core, well cutting samples, archived lithologic descriptions, and borehole geophysical logs for selected wells. The 35 test wells drilled during this study were deemed to be most useful (fig. 1 and table 1). Lithostratigraphic units mapped in Broward and Miami-Dade Counties are based largely on lithologic description and sections presented by Causaras (1985; 1987). Other geologic information was obtained from files of the USGS. Lithologic core descriptions prepared in this study are presented in appendix II, and thin-section rock-sample descriptions are provided in appendix III.

Peace River Formation

In southern Florida, the Hawthorn Group includes the Arcadia Formation that is principally composed of carbonate rocks and the Peace River Formation that is principally composed of siliciclastics. At the type area in DeSoto County, Fla., the Peace River Formation, which is sandwiched between the Tamiami and Arcadia Formations, consists of interbedded quartz sand, clay, and carbonate rocks with siliciclastic sediment composing two-thirds or more of the formation (Scott, 1988). The quartz sand contains a highly variable concentration of phosphate grains that ranges from a trace to 40 percent. The Peace River Formation ranges in age from late Miocene to early Pliocene (Missimer, 1997).

This study limited its scope within the Hawthorn Group to evaluating the lithologic and stratigraphic character of the upper part of the Peace River Formation. In ascending order, three lithofacies were identified in the upper part of the Peace River Formation: (1) diatomaceous mudstone, (2) terrigenous mudstone, and (3) clay-rich quartz sand. These lithofacies are characterized in table 3, and examples are shown in the thin sections in figure 5. The diatomaceous mudstone facies is underlain by quartz sand of the Peace River Formation, and in most of the study area, the clay-rich quartz sand facies of the Peace River Formation is overlain by less clay-rich quartz sand and sandstone of the unnamed formation and locally by the Ochopee Limestone. Continuous core samples show that, where present, the diatomaceous mudstone facies ranges from 0.1 to 18 ft in thickness; the terrigenous mudstone facies ranges from 2 to 28 ft in thickness; and the clay-rich quartz sand facies ranges from 0.5 to 75 ft in thickness. The Peace River Formation is distinguished from the unnamed formation by typically finer grain size and more silt and clay. Weedman and others (1999) used similar criteria. In the far western part of the study area, rock and sediment of the Peace River Formation grade laterally into sand of the unnamed formation.

Study of foraminifera from test wells C-1169, C-1182, and PB-1703 (fig. 1) by L.A. Guertin (Mary Washington College, oral commun., 1999) suggests that the Peace River Formation was deposited in a marine shelf depositional environment. Scott (1988) suggested open-marine conditions during deposition of the Peace River Formation in southeastern Florida. The present-day slope of the siliciclastic shelf profile within the study area is less than 1.0 degree in a paleobasinward direction, which was to the east or southeast. The upward transition from mudstones to quartz sand records an upward coarsening of grain size, an upward decrease in pelagic sedimentation, and an upward increase in siliciclastic sediment supply. These relationships represent a seaward shift in the vertical stacking of lithofacies related to a decrease in relative sea level.

Series	Lithostratigraphic units		Approximate thickness (feet)	Lithology	Hydrogeologic unit		Approximate thickness (feet)
HOLOCENE	UNDIFFERENTIATED	LAKE FLIRT MARL, UNDIFFERENTIATED SOIL AND SAND	0 - 5	Marl, peat, organic soil, quartz sand	SURFICIAL AQUIFER SYSTEM	WATER TABLE AQUIFER	0 - 120
PLEISTOCENE	UNDIFFERENTIATED	PAMLICO SAND	0 - 50	Quartz sand	SURFICIAL AQUIFER SYSTEM	WATER TABLE AQUIFER / BISCAYNE AQUIFER	
PLEISTOCENE	UNDIFFERENTIATED	MIAMI LIMESTONE	0 - 30	Oolitic limestone	SURFICIAL AQUIFER SYSTEM	WATER TABLE AQUIFER / BISCAYNE AQUIFER	
PLEISTOCENE	UNDIFFERENTIATED	FORT THOMPSON FORMATION	0 - 100	Marine limestone and minor gastropod-rich freshwater limestone	SURFICIAL AQUIFER SYSTEM	WATER TABLE AQUIFER / BISCAYNE AQUIFER	
PLEISTOCENE	UNDIFFERENTIATED	ANASTASIA FORMATION	0 - 140	Coquina, quartz sand and sandy limestone	SURFICIAL AQUIFER SYSTEM	WATER TABLE AQUIFER / BISCAYNE AQUIFER	
PLEISTOCENE	UNDIFFERENTIATED	KEY LARGO LIMESTONE	0 - 20	Coralline reef rock	SURFICIAL AQUIFER SYSTEM	WATER TABLE AQUIFER / BISCAYNE AQUIFER	
PLIOCENE	TAMIAMI FORMATION	PINECREST SAND MEMBER	0 - 90	Quartz sand, pelecypod-rich quartz sandstone, terrigenous mudstone	SURFICIAL AQUIFER SYSTEM	UPPER SEMICONFINING TO CONFINING UNIT	0 - 130
PLIOCENE	TAMIAMI FORMATION	OCHOPEE LIMESTONE MEMBER	0 - 130	Pelecypod lime rudstone and floatstone, pelecypod-rich quartz sand, moldic quartz sandstone	SURFICIAL AQUIFER SYSTEM	GRAY LIMESTONE AQUIFER	0 - 130
MIOCENE	UNNAMED FORMATION		0 - 300	Moldic pelecypod-rich quartz sand or sandstone	SURFICIAL AQUIFER SYSTEM	LOWER SEMICONFINING UNIT	0 - 20
MIOCENE	UNNAMED FORMATION			Quartz sand, sandstone, and pelecypod-rich quartz sand, local abundant phosphate grains	SURFICIAL AQUIFER SYSTEM	SAND AQUIFER(S)	0 - 100
MIOCENE	UPPER HAWTHORN GROUP	PEACE RIVER FORMATION	0 - 300	Clay-rich quartz sand, terrigenous mudstone, diatomaceous mudstone, local abundant phosphate grains	INTERMEDIATE CONFINING UNIT OR INTERMEDIATE AQUIFER SYSTEM		300±

Figure 4. Lithostratigraphic units recognized in the study area, their generalized geology, and relationship with hydrogeologic units. Modified from Olsson (1964), Hunter (1968), Miller (1990), Missimer (1992), and Weedman and others (1999).

Table 3. Lithofacies characteristics of the Peace River Formation

[Visual estimation was made for porosity; hydraulic conductivity was visually estimated by using a classification scheme from Fish (1988, table 8). Colors in the lithologic description refer to Munsell rock-color chart (Geological Society of America, 1991)]

Characteristic	Lithologic description
	Clay-Rich Quartz Sand Facies
Depositional textures	Terrigenous clay-rich sand
Color	Mainly yellowish-gray 5Y 7/2 and 5Y 8/1, and light-gray-olive 5Y 6/1
Carbonate grains	Local thin-shelled pelecypods, oysters, *Turritella* and benthic foraminifers
Accessory grains	Common phosphate grains (trace to 40 percent); minor heavy minerals; trace mica
Grain size	Mainly very fine quartz grains; minor silt-size quartz grains and terrigenous mud; local micrite, fine sand-size to small pebble-size quartz grains and very fine sand-size to pebble-size phosphate grains
Porosity	Mainly intergrain; local moldic; ranges from 5 to 20 percent
Hydraulic conductivity	Mainly very low (less than 0.1 foot per day) to low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
	Terrigenous Mudstone Facies
Depositional textures	Terrigenous mudstone
Color	Mainly light-olive-gray 5Y 5/2, yellowish-gray 5Y 7/2, and olive-gray 5Y 4/1, 5Y 3/2
Carbonate grains	Local benthic foraminifers and pelecypod fragments
Accessory grains	Common quartz grains; local diatoms, phosphate grains, mica, fish scales, shark’s teeth
Grain size	Mainly terrigenous clay; minor silt-size quartz; local very fine sand- to granule-size quartz grains and very fine sand- to pebble-size phosphate grains
Porosity	Minor microporosity
Hydraulic conductivity	Very low (less than 0.1 foot per day)
	Diatomaceous Mudstone Facies
Depositional textures	Diatomaceous mudstone
Color	Mainly yellowish-gray 5Y 7/2 and light-olive-gray 5Y 5/2
Carbonate grains	Local benthic foraminifers
Accessory grains	Common quartz grains and local phosphate grains
Grain size	Mainly clay-size terrigenous clay and fine sand-size diatoms; minor silt-size quartz; local very fine sand-size quartz and phosphate grains, and fish scales
Porosity	Minor microporosity
Hydraulic conductivity	Very low (less than 0.1 foot per day)

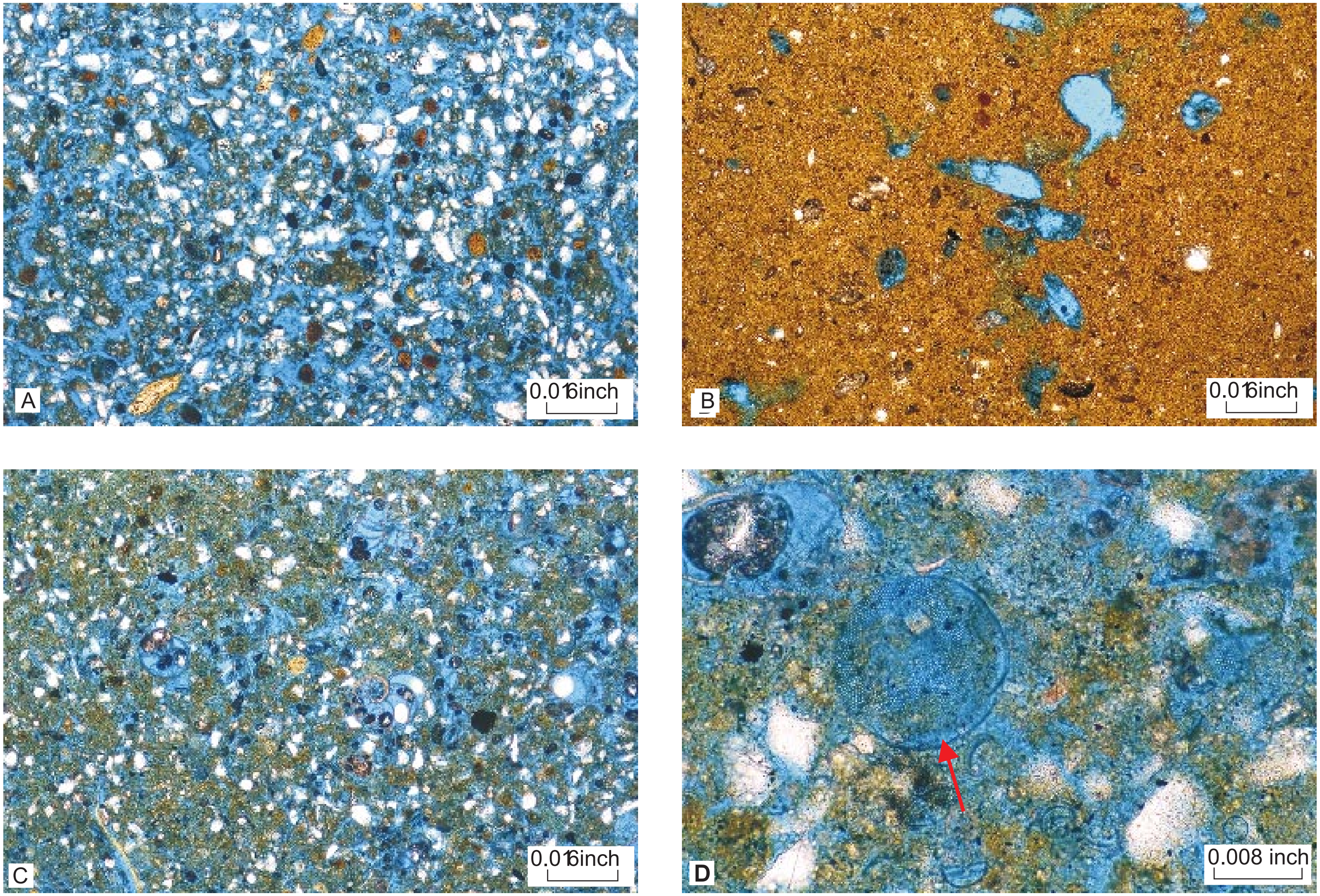


Figure 5. Thin-section photomicrographs showing lithofacies identified for the Peace River Formation. Samples collected from well C-1182. Photographs represent (A) sample HXP-22, terrigenous clay-rich quartz sand. Sample preparation has greatly increased original intergrain porosity; (B) sample HXP-23, benthic foram terrigenous mudstone; (C) sample HXP-24, diatomaceous terrigenous mudstone; and (d) enlarged view of sample shown in photo C (arrow points to a diatom). Plane-polarized light; blue epoxy highlights porosity. Appendix III presents complete description of rock samples.

Unnamed Formation

The boundary separating the base of the Tamiami Formation and the top of the Peace River Formation is poorly defined in much of southern Florida. Quartz sand and sandstone occur beneath the mixed carbonate and siliciclastic rock of the Tamiami Formation and above the clay-rich quartz sand of the Peace River Formation. This sand and sandstone has not as yet been assigned to a formally defined formation. Weedman and others (1997), Edwards and others (1998), and Weedman and others (1999) included these unnamed sediments as part of an informal "unnamed formation," anticipating clarification of its status following further study. The unnamed formation was defined by Weedman and others (1999, p. 15) as "variably phosphatic and fossiliferous combinations of quartz gravel, sand, and silt, clay, and carbonate rocks and sediment." For the present study (this report), the unnamed formation is defined as relatively clay-free, quartz sand and sandstone underlying the lowest part of the Ochopee Limestone. At the base of the unnamed formation, relatively clean quartz sand overlies clay-rich siliciclastics of the Peace River Formation. Thus, definition of the unnamed formation includes the siliciclastic interval previously included in the lower part of the Tamiami Formation (Causaras, 1985; 1987) and the Miocene coarse clastics (Knapp and others, 1986; Smith and Adams,1988). The unnamed formation is probably equivalent, in part, to the Long Key Formation (Cunningham and others, 1998) of the Florida Keys south of the study area. The unnamed formation was not recognized by Missimer (1997), and the unit defined as the unnamed formation herein is included in the Peace River Formation by Missimer.

Two lithofacies can be differentiated within the unnamed formation, occurring as quartz sand and pelecypod-rich quartz sand or sandstone. These lithofacies are characterized in table 4, and examples are shown in thin sections in figure 6. The pelecypod-rich facies locally contains abundant *Turritella* gastropod molds and occurs locally beneath the base of the Ochopee Limestone; it is invariably underlain by the quartz sand facies. The unnamed formation was probably deposited in a marine siliciclastic-shelf depositional environment. Indicators of depositional environments include: (1) local presence of marine fossils, (2) absent or minor clay content suggesting deposition above fair-weather wave base, and (3) probably partial equivalency to Peace River beds containing foraminifera that indicate a marine shelf depositional environment (L.A. Guertin, Mary Washington College, oral commun., 1999). The

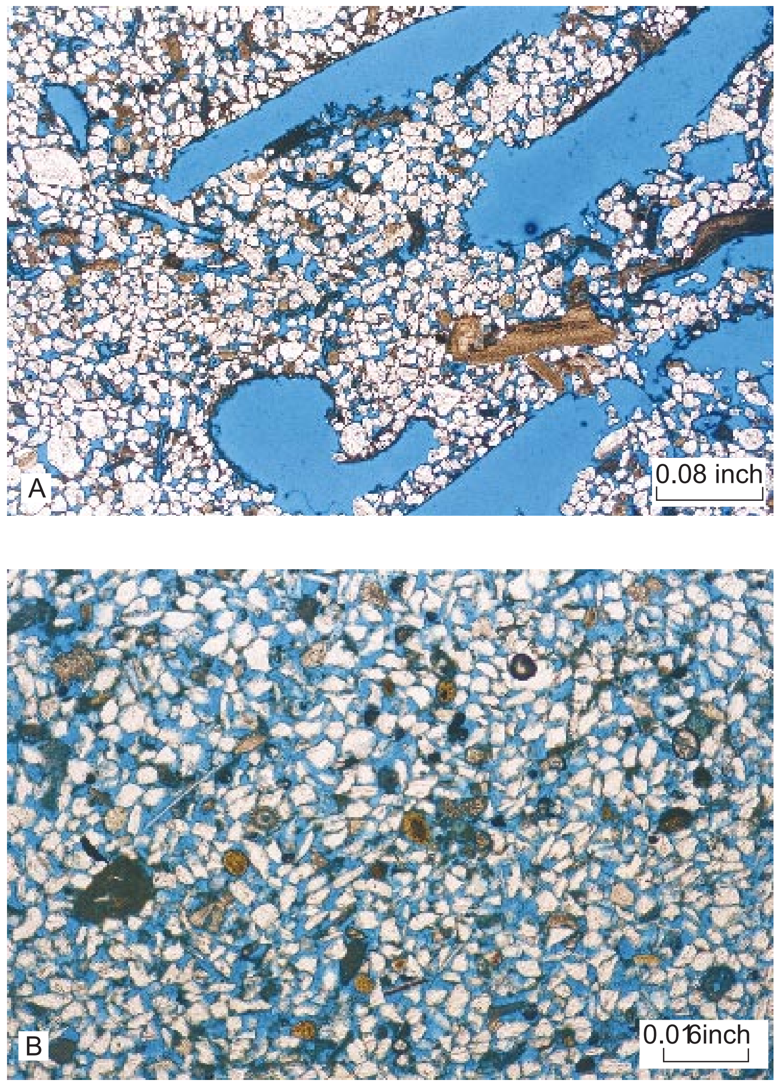


Figure 6. Thin-section photomicrographs showing lithofacies identified for the unnamed formation. Photographs represent (A) sample HHW-2 from well C-1141, pelecypod-rich quartz sand or sandstone showing moldic and integrain porosity; and (B) sample HXP-21 from well C-1182, quartz sand showing integrain porosity. Plain-polarized light; blue epoxy highlights porosity. Original integrain porosity probably increased during sample preparation. Appendix III presents complete description of rock samples.

Table 4. Lithofacies characteristics of the unnamed formation

[Visual estimation was made for porosity; hydraulic conductivity was visually estimated by using a classification scheme from Fish (1988, table 8). Colors in the lithologic description refer to Munsell rock-color chart (Geological Society of America, 1991)]

Characteristic	Lithologic description
Pelecypod-Rich Quartz Sand or Sandstone Facies	
Depositional textures	Quartz sand matrix with pelecypod rudstone framework, or quartz sand supporting skeletal floatstone
Color	Mainly yellowish-gray 5Y 8/1 and 5Y 7/2; locally light-gray N7 to white N9, light-olive-gray 5Y 5/2, light-olive-gray 5Y 6/1, and very pale orange 10YR 8/2
Carbonate grains	Pelecypods (including *Pecten* and oysters), undifferentiated skeletal grains, gastropods (including *Turritella*), bryozoans, serpulids, and echinoids
Accessory grains	Trace to 40 percent phosphate and heavy mineral grains; local minor terrigenous clay and lime mudstone; local trace mica
Grain size	Mainly very fine to fine quartz sand; ranges from silt to very coarse quartz sand; carbonate grains range from silt to cobble size; local terrigenous clay
Porosity	Intergrain and moldic; ranges from 5 to 25 percent; local abundant pelecypod molds contribute to high porosity
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from very low (less than 0.1 foot per day) to high (100 to 1,000 feet per day); local abundant pelecypod molds contribute to high hydraulic conductivity
Quartz Sand Facies	
Depositional textures	Quartz sand with less than 10 percent skeletal grain
Color	Mainly yellowish-gray 5Y 8/1 and yellowish-gray 5Y 7/2; locally medium-dark-gray N4 to very light gray N8, light-olive-gray 5Y 5/2, grayish-yellow-green 5GY 7/2, pale-olive 10Y 6/2, very pale orange 10YR 8/2, and pale-yellowish-brown 10YR 6/2
Carbonate grains	Pelecypods (local *Pecten* and *Chione*), benthic foraminifers, echinoids, and undifferentiated skeletal grains
Accessory grains	Trace to 30 percent phosphate and heavy mineral grains; local minor terrigenous clay; local trace mica; trace to 1 percent plagioclase; trace microcline
Grain size	Mainly very fine to medium quartz sand; ranges from silt to granule size; carbonate grains range from silt to pebble size; terrigenous clay
Porosity	Intergrain; ranges from 5 to 20 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)

upward transition of the two lithofacies represents an upward decrease in supply of quartz sand relative to local supply of carbonate grains. The eastward gradation from relatively clean quartz sand of the unnamed formation to clay-rich sands and mudstone of the Peace River Formation in the far western part of the study area indicates an eastward deepening of the marine siliciclastic shelf.

The unnamed formation occurs throughout most of the study area, bounded at its top by the Ochopee Limestone and at its base by the Peace River Formation or the Arcadia Formation. The contact between the unnamed formation and the Ochopee Limestone, as indicated by core samples and borehole geophysical logs, appears to be sharp in some areas; in other areas, it is gradational with some interfingering of limestone and quartz sand or sandstone over a short interval. In southwestern Florida, Missimer (1999) recognized an unconformity representing a 0.2 million year hiatus between the top of the Peace River Formation and overlying Tamiami Formation. This unconformity may be equivalent to the contact between the unnamed formation and Ochopee Limestone. On the basis of continuous core data collected during this study, the unnamed formation is locally absent, but increases to as much as 306 ft in thickness at well C-1163 in northwestern Collier County (fig. 1), where the unnamed formation lies directly on the Arcadia Formation.

Tamiami Formation

The "Tamiami limestone" was named informally by Mansfield (1939) to describe sandy limestone that crops out along the northern side of Tamiami Trail in Collier County. He reported the Tamiami as a "light-gray to white, hard, sandy limestone containing abundant identifiable mollusk molds and well preserved pectens, oysters, barnacles, and echinoids." The Tamiami Formation was redefined by Parker (1951, p. 823) to include all upper Miocene deposits in southern Florida. Description and definition of the Tamiami Formation have varied over the past 50 years (Parker and others, 1955; McCoy, 1962; Klein and others, 1964; Hunter, 1968; Missimer, 1978; Peck and others, 1979; Hunter and Wise, 1980; and Missimer, 1992), and the precise upper and lower boundaries remain problematic (Missimer, 1992).

Hunter (1968) formally proposed three members, all equivalent in age, to the upper Tamiami Formation: (1) Ochopee Limestone Member, (2) Pinecrest Sand Member, and (3) Buckingham Limestone Member. Hunter further divided the lower Tamiami Formation into two members: Murdock Station Member and Bayshore Clay Member. Hunter and Wise (1980) proposed that the Tamiami Formation be restricted to include the Ochopee and Buckingham Limestones and equivalent facies, such as the Pinecrest Sand. They further suggested that subjacent units be included as part of the Peace River Formation, which is in agreement with additional definition of the Peace River Formation by Scott (1988). For the present study, only the Ochopee Limestone and Pinecrest Sand Members could be identified, and in most of the study area the unnamed formation has been mapped underlying the Ochopee Limestone. Further refinement of core data collected during this study could show that other members of the Tamiami Formation are present.

Missimer (1992) estimated the age of the Tamiami Formation to be Pliocene (4.2 to 2.8 million years ago), using paleontologic data and interpretation of an established global sea-level curve. Edwards and others (1998) assigned the Ochopee Limestone of western Collier County to an early Pliocene age, but possibly ranging from late Miocene to late Pliocene. Age designations of Edwards and others (1998) were based on strontium-isotope chemostratigraphy and biostratigraphy (dinocysts and molluscan assemblages). Weedman and others (1999) suggested an early Pliocene age for the Tamiami Formation in eastern Collier and northern Monroe Counties; however, some age dating provided in that study are consistent with late Pliocene age.

Ochopee Limestone Member

The Ochopee Limestone includes a regionally extensive limestone facies of the Tamiami Formation that can be mapped beneath most of Collier County and parts of Lee, Hendry, Miami-Dade, Monroe, and Broward Counties (Hunter, 1968). Missimer (1992) characterized the Ochopee Limestone Member as containing very fine to fine sand-size quartz grains (5 to 80 percent), commonly with an increase in the quartz sand to limestone ratio with depth. In western Broward and western Miami-Dade Counties, Causaras (1985; 1987) recognized a gray limestone unit within the lower part of the Tamiami Formation, within which Fish (1988) and Fish and Stewart (1991) later defined the gray limestone aquifer.

The Ochopee Limestone was delineated by Weedman and others (1997), Edwards and others (1998), and Weedman and others (1999) for the Collier County part of the study area. Well-to-well correlation shown herein indicates that the Ochopee Limestone is equivalent to limestone of the lower Tamiami Formation in western Collier County (Knapp and others, 1986), Hendry County (Smith and Adams, 1988), and Broward and Miami-Dade Counties (Causaras 1985; 1987). The Ochopee Limestone may be equivalent, in part, to the Long Key and Stock Island Formations that occur in the Florida Keys (Cunningham and others, 1998).

Two lithofacies characterize the Ochopee Limestone Member: (1) pelecypod lime rudstone or floatstone, and (2) pelecypod-rich quartz sand or sandstone. The lithofacies are characterized in table 5, and examples of thin sections are shown in figure 7. The pelecypod lime rudstone or floatstone facies is the most common lithofacies, whereas the pelecypod-rich quartz sand or sandstone facies occurs only locally as thin to thick beds (fig. 1, wells C-1141, C-1178, HE-1110, and PB-1703). Skeletal carbonate grains of the pelecypod lime rudstone or floatstone lithofacies include pelecypods (local oysters, *Pecten*, *Chione*, and *Ostrea*), undifferentiated skeletal fragments, bryozoans, gastropods (local *Turritella* and *Vermicularia*), benthic foraminifera, echinoids, serpulids, barnacles, planktic foraminifera, ostracods, encrusting foraminifera, and ahermatypic corals. In the pelecypod-rich quartz sand or sandstone lithofacies, quartz sand is typically very fine to fine grained, but locally may range from silt to very coarse sand.

The Ochopee Limestone was deposited in a carbonate ramp depositional system (Burchette and Wright, 1992; Cunningham and Reese, 1998). Criteria to support this interpretation include: (1) a low depositional gradient of less than 1 degree, (2) widespread continuity of facies patterns, and (3) an almost complete absence of internal exposure surfaces. In the study area, most mixed-siliciclastic-carbonate rocks of the Ochopee Limestone were deposited in a mid-ramp depositional environment as defined by Burchette and Wright (1992), and the direction of dip of the ramp was generally to the east or southeast. Evidence for this depositional environment is indicated by the common occurrence of coarse-grained lime rudstone that has a well washed, grain-dominated matrix (Lucia, 1995) and lime mud-rich floatstone. The mixture of these grain-dominated and mud-dominated carbonates and lack of shallow-water indicators suggest deposition below fair-weather wave base (FWWB) but above storm wave base (SWB). This zone between FWWB and SWB defines the mid-ramp depositional environment (Burchette and Wright, 1992). The occurrence of regional-scale facies patterns in the Ochopee Limestone ramp suggest predictable hydraulic properties.

The benthic-carbonate grains of the Ochopee Limestone represent a heterozoan particle association, which James (1997) defined as a group of carbonate particles produced by light-independent benthic organisms that may or may not contain red calcareous algae. Red algae were not observed in the Ochopee Limestone within the study area. Their absence combined with a predominately heterozoan particle association and lack of shallow-marine particles, such as ooids, is consistent with relatively deep, noneuphotic, temperate bottom-water conditions. An almost complete absence of exposure surfaces within the Ochopee suggests deposition at water depths sufficient to minimize changes in water-bottom conditions during low-amplitude changes in relative sea level.

At one test well in west-central Collier County (fig. 1, well C-1178), the Ochopee Limestone is bounded at its top by a subaerial exposure “zone” that extends to a depth of 30 ft below the upper bounding surface of the Ochopee. Root molds lined with calcrete are common within this thick zone. The exposure zone contains a record of at least two emersions due to relative falls in sea level, possibly caused by very local tectonic flexure of the Ochopee seafloor.

The age dating by Weedman and others (1999) and the vertical facies analysis described above suggest that the Ochopee Limestone may have been deposited during transgressive to high-stand conditions (as defined by Haq and others, 1988) of the early Pliocene. During this time, the Florida Platform was flooded, siliciclastic supply had diminished, and water depth and climate created bottom conditions favorable to light-independent animals.

The Ochopee Limestone is comparatively uniform in thickness in southern Florida, generally ranging between 30 and 100 ft. The unit is thickest in a widespread area that extends across southwestern Palm Beach, northwestern Broward, and southern Hendry Counties where it attains 130 ft in thickness. South of the Tamiami Trail in Miami-Dade County, the Ochopee Limestone pinches out to the southeast where it merges with siliciclastics of the overlying Pinecrest Sand and underlying unnamed formation. The southeastern limit of the “Ochopee” ramp is about coincident with the southern boundary of the study area. The eastern limit is approximately coincident with the eastern boundary of the gray limestone aquifer that underlies eastern Miami-Dade and Broward Counties.

Table 5. Lithofacies characteristics of the Ochopee Limestone Member of the Tamiami Formation

[Visual estimation was made for porosity; hydraulic conductivity was visually estimated by using a classification scheme from Fish (1988, table 8). Colors in the lithologic description refer to Munsell rock-color chart (Geological Society of America, 1991)]

Characteristic	Lithologic description
Pelecypod Lime Rudstone or Floatstone Facies	
Depositional textures	Pelecypod lime rudstone or floatstone with quartz sand-rich lime packstone or grainstone matrix
Color	Mainly medium-light-gray N6 to very light gray N8 and yellowish-gray 5Y 8/1; locally yellowish-gray 5Y 7/2, black to medium-gray N5, white N9, and very pale orange 10YR 8/2
Carbonate grains	Pelecypods (local oysters, *Pecten*, *Chione*, and *Ostrea*), undifferentiated skeletal fragments, bryozoans, gastropods (local *Turritella* and *Vermicularia*), benthic foraminifers, echinoids, serpulids, barnacles, planktic foraminifers, ostracods, encrusting foraminifers, corals (ahermatypic)
Accessory grains	Common quartz sand and phosphate grains
Grain size	Carbonate grains range from silt to cobble size; quartz sand mainly very fine to fine, ranges from silt to very coarse
Porosity	Mainly intergrain and moldic; local intrafossil and boring; ranges from 5 to 25 percent
Hydraulic conductivity	Mainly moderate (10 to 100 feet per day); ranges from low (0.1 to 10 feet per day) to high (100 to 1,000 feet per day)
Pelecypod-Rich Quartz Sand or Sandstone Facies	
Depositional textures	Pelecypod-rich quartz sand and quartz-rich sandstone
Color	Mainly yellowish-gray 5Y 8/1 and light-gray N7 to very light gray N6; locally medium-dark-gray N4 to medium-light-gray N6, very pale orange 10YR 8/2, light-olive-gray 5Y 6/1, yellowish-gray 5Y 7/2, and pale-yellowish-brown 10YR 6/2
Carbonate grains	Pelecypods (local oysters), undifferentiated skeletal fragments, gastropods, echinoids, barnacles, serpulids, intraclasts, bryozoans, and encrusting foraminifers
Accessory grains	Absent to 5 percent phosphate and heavy mineral grains; local minor terrigenous clay or lime mudstone matrix
Grain size	Mainly very fine to fine quartz sand; ranges from silt to coarse quartz sand; carbonate grains range from silt to cobble size
Porosity	Mainly intergrain with local moldic and intragrain; ranges from 10 to 20 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day)

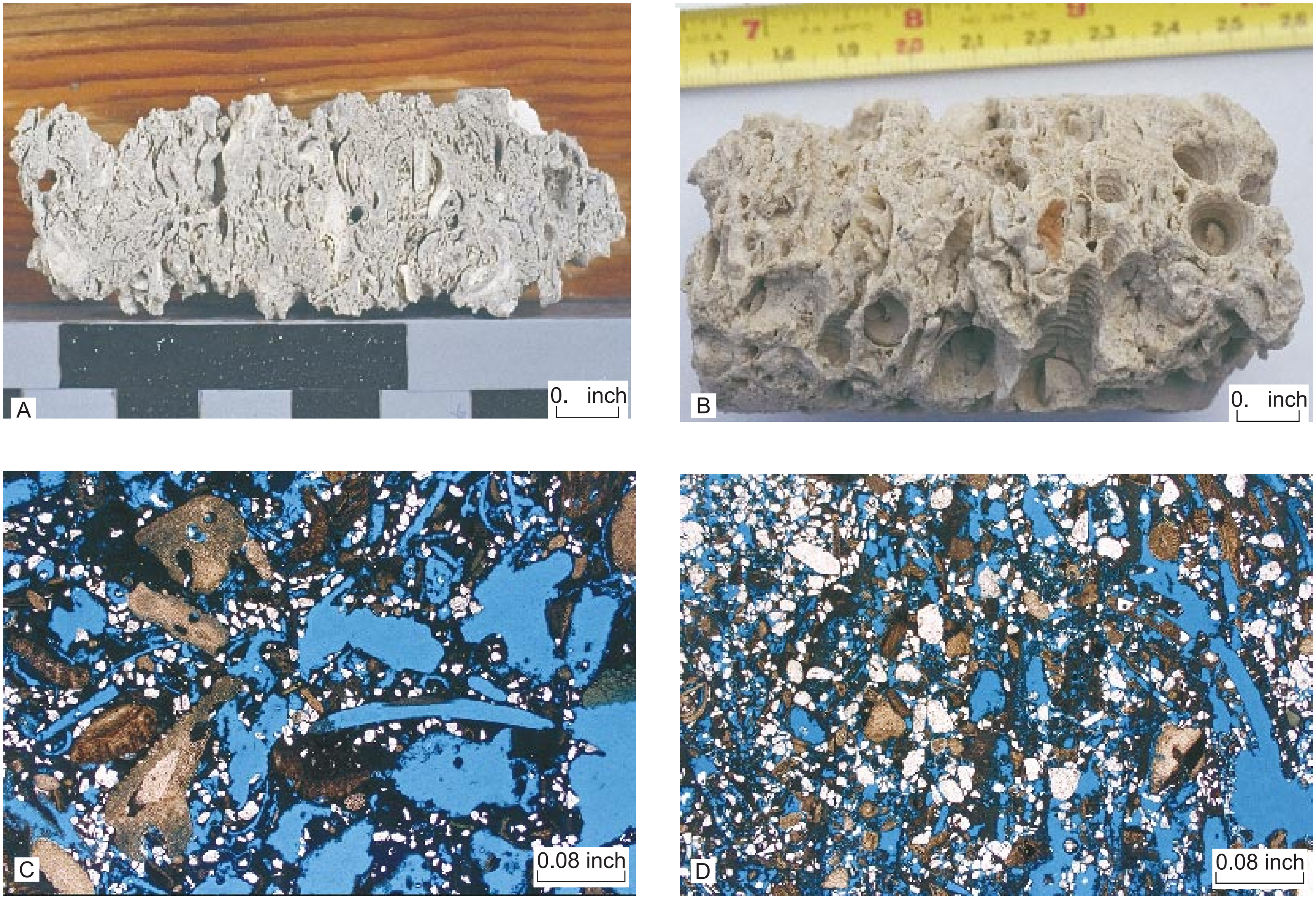


Figure 7. Core photographs and thin-section photomicrographs of the pelecypod lime rudstone facies of the Ochopee Limestone Member of the Tamiami Formation. Photographs represent (A) sample from well C-1142 from a depth of 73.5 feet below land surface, core slab with moldic porosity in a pelecypod lime rudstone; (B) sample from well HE-1113 from a depth of 49 feet below land surface, whole core with moldic porosity of a *Turritella* rudstone; (C) sample HHW-20 from well C-1181, pelecypod-rich quartz sandstone with lime mud matrix; and (D) sample HHW-4 from well C-1142, pelecypod quartz sand-rich lime packstone. Plane-polarized light; blue epoxy highlights porosity. Appendix III presents complete thin-section descriptions of photos C and D.

Pinecrest Sand Member

The name Pinecrest Sand Member is derived from the "Pinecrest beds" informally described by Olsson (1964) for a faunal assemblage found along Tamiami Trail near the boundary between Collier and Miami-Dade Counties. Missimer (1992) defined the Pinecrest Sand as a sand and shell unit. In southwestern Florida, he recognized it as occurring discontinuously and only in small areas, commonly less than 1 mi^2 (square mile) in size. Weedman and others (1999) recognized the Pinecrest Member overlying the Ochopee Limestone in northeasternmost Monroe County.

Three lithofacies have been differentiated within the Pinecrest Sand Member: (1) a quartz sand facies, (2) a pelecypod lime rudstone and floatstone facies, and (3) a terrigenous mudstone facies. These lithofacies are characterized in table 6, and examples of thin sections are shown in figure 8. The quartz sand facies is characteristic of most of the Pinecrest Sand. The terrigenous mudstone facies occurs mainly in the north-central part of the study area where it typically occurs as one or two beds within the lower part of the Pinecrest Sand. The pelecypod lime rudstone is found only very locally as discrete beds within or near the top of the Pinecrest Sand. Foraminiferal analyses by L.A. Guertin (Mary Washington College, oral commun., 1999) of test well PB-1703 (fig. 1) in Palm Beach County indicate deposition of the Pinecrest Sand Member in a marine siliclastic shelf.

The Pinecrest Sand ranges from 20 to 60 ft in thickness in most of the study area. The Pinecrest is thickest (125 ft) in central and south-central Miami-Dade County. Other areas where the Pinecrest Sand is thick were mapped in southern Hendry, northeastern Collier, west-central Broward, and south-central Palm Beach Counties. The Pinecrest Sand pinches out in the western part of the study area: Monroe, Collier and Hendry Counties. In southern Miami-Dade County, the Pinecrest Sand merges with siliciclastics of the Long Key Formation (Cunningham and others, 1998) in the Florida Keys.

Post-Pliocene Formations

The Fort Thompson Formation (as defined by Causaras, 1987) was penetrated in test wells C-1135 and MO-178 in southeastern Collier County and northeastern Monroe County (fig. 1). Limestone units in these wells were identified as Fort Thompson Formation based on: (1) presence of calcrete (Perkins, 1977), (2) marine pelecypod limestone lithology (Causaras, 1987), and (3) occurrence of Miami Limestone above the Fort Thompson Formation in well MO-178. These units are composed of pelecypod lime floatstone with a quartz sandstone matrix or a skeletal, quartz sand-rich, lime packstone matrix. The rock contains 10 to 70 percent quartz grains. Porosity ranges from 15 to 20 percent; however, estimated hydraulic conductivity is low. In well MO-178, the top of the Fort Thompson Formation is bounded by a 0.75-ft thick quartz-sand-rich calcrete and the formation is 5.75 ft thick. The top of this calcrete layer could be equivalent to the upper surface of the Q3 unit of Perkins (1977).

Beds possibly equivalent to the Fort Thompson Formation were penetrated in test well PB-1704 in southeastern Palm Beach County (fig. 1) from a depth of 5.5 to 49.5 ft below land surface. These beds combine to form at least seven high-frequency, vertically stacked, marine-to-lacustrine, sedimentary cycles that range from 2 to 14 ft in thickness. The base of each cycle is composed of marine inner shelf, restricted bay or lagoon, or marine tidal flat deposits. Each cycle is capped with subaerially exposed lacustrine lime mudstone or marl, which typically contains root molds and desiccation cracks, and rarely calcrete. Low-spired *Helisoma* gastropods are common in the lacustrine deposits, which are characteristic of the Fort Thompson Formation (Perkins, 1977; Causaras, 1987).

The Miami Limestone, as defined by Hoffmeister and others (1967), was penetrated in well MO-178 (fig. 1). Here, the 0.75-ft thick Miami Limestone is exposed at land surface. The Miami Limestone is a pelecypod lime floatstone with a pelmoldic grainstone and packstone matrix. Pelecypods and molds of peloids are abundant; gastropods and the cheilostome bryozoan *Schizoporella* are uncommon. This unit is considered to be part of the bryozoan facies described by Hoffmeister and others (1967), and this occurrence lies within the western mapped limit of the Miami Limestone in northernmost Monroe County.

The Lake Flirt Marl, as defined by Sellards (1919), was penetrated only in well C-1141 in east-central Collier County and well PB-1704 in southwestern Palm Beach County (fig. 1). The thickness of the unit in the two wells ranges from 2 to 3 ft. The Lake Flirt Marl is composed of silty marl or quartz sand with a marl matrix. DuBar (1958) and Klein and others (1964) described similar deposits in southwestern Florida that they assign to the Lake Flirt Marl. Porosity is predominately intergranular microporosity with local root-mold and desiccation-crack porosity. Visual estimates indicate very low hydraulic conductivity. The localized areal distribution of the unit and the occurrence of root molds and desiccation cracks are consistent with accumulation within freshwater lakes.

Table 6. Lithofacies characteristics of the Pinecrest Sand Member of the Tamiami Formation

[Visual estimation was made for porosity; hydraulic conductivity was visually estimated by using a classification scheme from Fish (1988, table 8). Colors in the lithologic description refer to Munsell rock-color chart (Geological Society of America, 1991)]

Characteristic	Lithologic description
Quartz Sand Facies	
Depositional textures	Quartz sand with locally abundant fossils
Color	Mainly yellowish-gray 5Y 8/1 and yellowish-gray 5Y 7/2; locally medium-gray N5 to very light gray N8, very pale orange 10YR 8/2, light-olive-gray 5Y 6/1, light-olive-gray 5Y 5/2, grayish-yellow 5Y 8/4, grayish-orange 10YR 7/4, and dark-yellowish-orange 10 YR 6/6
Carbonate grains	Pelecypods (local oysters), undifferentiated skeletal fragments, echinoids, serpulids, bryozoans, and benthic and planktic foraminifers
Accessory grains	Trace to 3 percent phosphate and heavy mineral grains; local trace mica; local minor terrigenous clay
Grain size	Mainly very fine to fine quartz sand; ranges from silt to very coarse quartz sand; carbonate grains range from silt to pebble size
Porosity	Mainly intergrain and local intragrain, ranges from 5 to 25 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
Pelecypod Lime Rudstone and Floatstone Facies	
Depositional textures	Pelecypod lime rudstone or floatstone with quartz sand-rich lime packstone and grainstone matrix
Color	yellowish-gray 5Y 8/1, medium-gray N5 to light-gray N7, very pale orange 10YR 8/2, pale-yellowish-brown 10YR 6/2
Carbonate grains	Pelecypods, undifferentiated skeletal fragments, gastropods, oysters, serpulids, bryozoans, cerithiids, and echinoids
Accessory grains	Trace to 3 percent phosphate and heavy mineral grains
Grain size	Carbonate grains up to pebble size; quartz sand mainly very fine to fine and ranges from silt to coarse size
Porosity	Mainly intergrain and moldic; local intragrain and shelter; ranges from 5 to 15 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
Terrigenous Mudstone Facies	
Depositional textures	Silty terrigenous mudstone to quartz sand-rich terrigenous mudstone; locally grades into terrigenous clay-rich lime mudstone
Color	Light-olive-gray 5Y 5/2, light-olive-gray 5Y 6/1 and yellowish-gray 5Y 8/1; locally pale-olive 10Y 6/2, light-olive-gray 5Y 6/1, dusky-yellow-green 5GY 5/2, and yellowish-gray 5Y 7/2
Carbonate grains	Pelecypods (local oysters), benthic and planktic foraminifers, undifferentiated skeletal fragments, and fish scales
Accessory grains	Locally common quartz grains; trace to 1 percent phosphate grains; trace to 3 percent heavy mineral grains; local trace mica; trace plagioclase and microcline
Grain size	Mainly terrigenous clay; quartz grains range from silt to fine sand size; local medium to coarse quartz sand
Porosity	Intergrain; less than or equal to 5 percent
Hydraulic conductivity	Very low (less than 0.1 foot per day)

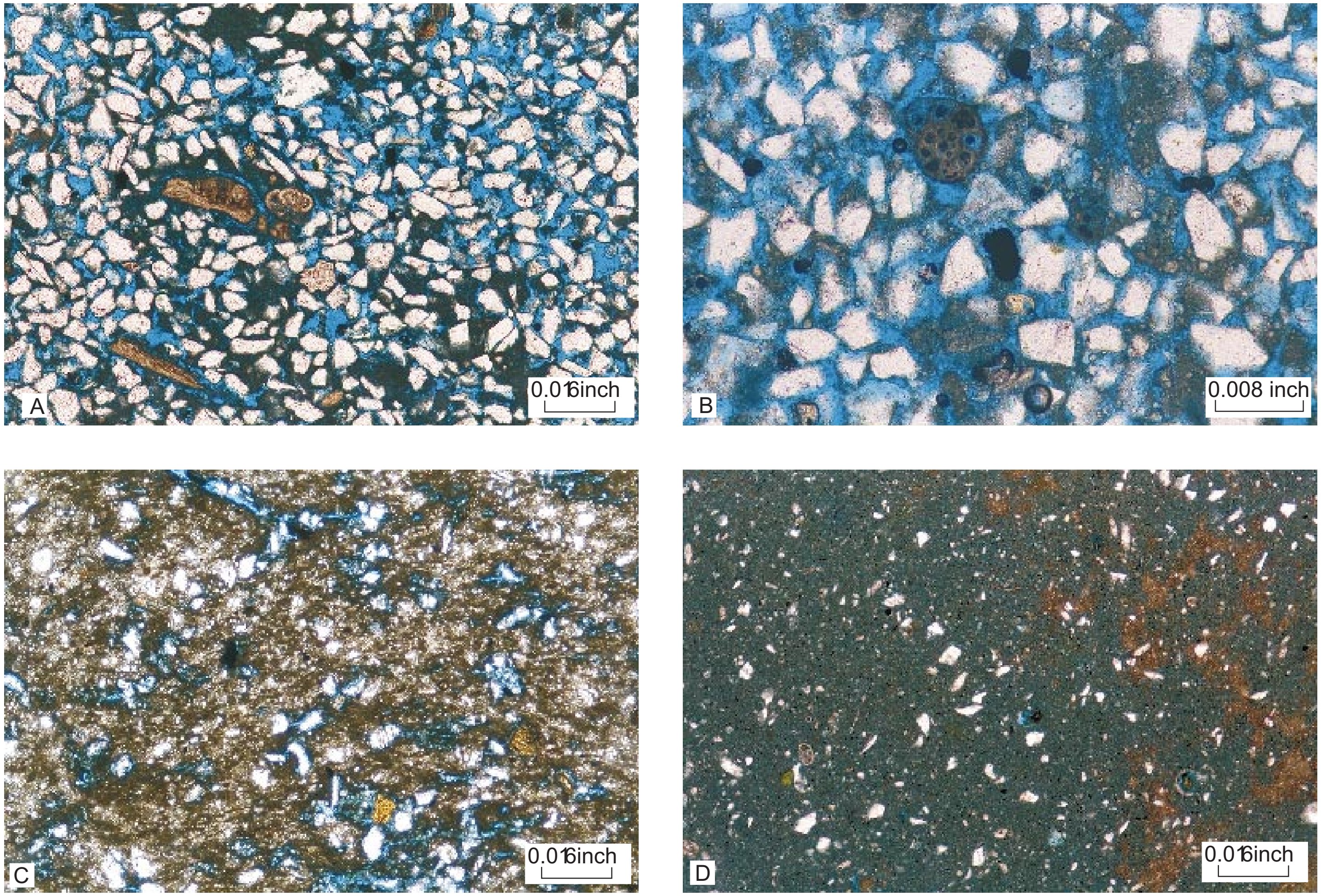


Figure 8. Thin-section photomicrographs showing lithofacies identified for the pinecrest Sand Member of the Tamiami Formation. Photographs represent (A) sample HXP-1 from well C-1183, fine quartz sand; (B) sample HXP-18 from well C-1182, very fine to fine quartz sand; (C) sample HXP-19 from well C-1182, terrigenous mudstone; and (D) sample HXP-2 from well C-1183, lime mudstone. Non-effective moldic porosity is shown. Original intergrain porosity slightly increased during sample preparation for A, B, and C. Plain-polarized light; blue epoxy highlights porosity. Appendix III presents complete description of rock samples.

Structure

Four hydrogeologic sections show lithostratigraphic units and structure in the study area. Their traces are shown in figure 9. Hydrogeologic sections A-A′ and A′-A″ extend northwest to southeast from southern Hendry County to southern Miami-Dade County (figs. 10 and 11). Hydrogeologic sections B-B′ and C-C′ extend west to east along Alligator Alley and Tamiami Trail, respectively (figs. 12 and 13).

The configuration of the top and base of the gray limestone aquifer (figs. 14 and 15) approximately conforms to the upper and lower boundaries of the Ochopee Limestone (figs. 10-13), respectively. Accordingly, the top and base of the aquifer are used herein to discuss the structural setting of the study area. The criteria used for determining the boundaries of the aquifer are presented later in the report. The depths below land surface of these boundaries in selected wells are given in table 7.

In the northern part of the study area in Hendry, Palm Beach, Collier and Broward Counties, comparison of the base of the gray limestone aquifer (fig. 15) and the top of the Arcadia Formation (Cunningham and others, 1998, fig. 17b) indicates similar structural configuration of both marker horizons. Two southeastward plunging synclines mapped at the top of the Arcadia Formation are approximately mirrored by the base of the gray limestone aquifer as shown in fig. 15. One structurally low area at the base of the aquifer lies in west-central Collier County (fig. 15, wells C-913 and C-1178), and the other extends through the intersection of Hendry, Palm Beach, and Broward Counties (fig. 15). Similarly, in the southern part of the study area, a southeast-to-southward plunging syncline at the Arcadia level (Cunningham and others, 1998, fig. 17b) coincides with an area where the altitude of the base of the gray limestone aquifer is low passing through well G-3677 (fig. 15).

In the northern part of the study area in Hendry, Palm Beach, Collier, and Broward Counties, areas of thick gray limestone aquifer (fig. 16) correspond to low areas mapped on the top of the Arcadia (Cunningham and others, 1998, fig. 17b). Additionally, in southeastern Hendry and eastern Collier Counties, a relatively thin area of the gray limestone aquifer trending northwest and passing through well HE-1113 (fig. 16) exists above a plunging anticline mapped at the top of the Arcadia. Correspondence in structural altitudes were not observed between the top of the Arcadia and the top of the gray limestone aquifer.

The coincidence between aquifer thickness, structural configuration at the base of the aquifer, and the structural attitude at the top of the Arcadia Formation suggests that Miocene paleotopography at the Arcadia level influenced deposition of the Ochopee Limestone. Comparison of maps shown herein and in Cunningham and others (1998) suggests accumulation of the Ochopee Limestone was thickest in paleotopographic low areas and thinnest in paleotopographic high areas. This hypothesis suggests that paleotopography played a role in controlling the thickness of the gray limestone aquifer. Alternatively, structural movements in parts of the study area may have occurred concurrent to Pliocene deposition of the Ochopee Limestone, permitting greater accumulation of carbonate sediment. This second hypothesis suggests structural movement may have locally influenced the thickness of the gray limestone aquifer in parts of the study area.

A northwest-southeast trending fault is suggested in eastern Collier County based on well-control data for the base of the gray limestone aquifer (fig. 15). Displacement could be as large as 60 ft. An offset of about 30 ft is indicated between two test wells along Alligator Alley, the Noble’s Road test well (C-1139) and the Sabine Road test well (fig. 15, C-1173), which is about 2,500 ft south of C-1139, and this offset is shown on hydrogeologic sections A-A′ and B-B′ (figs. 10 and 12). Two monitoring wells (C-1184 and C-1185) were installed in the gray limestone aquifer at the Noble’s Road site near well C-1139 (table 1). Well C-1185 is only about 60 ft west of C-1139, and well C-1184 is about 700 ft west of C-1139. On the basis of correlation between C-1184 and C-1185 using lithologic data and gamma-ray logs, it is postulated the fault is present between them and was active during deposition of the Ochopee Limestone and possibly the Pinecrest Sand (fig. 17). Both units are thicker in well C-1185 on the downthrown side of the fault. The thickening of these units between the wells could have resulted from differential erosional paleotopography of a subjacent unit prior to their deposition; however, the continuity in thickness of the lower semiconfining unit (unnamed formation) below the Ochopee Limestone (figs. 10 and 17) does not indicate erosion. If this fault is present, it is probably deep seated. It may not actually extend up as high as the Tamiami Formation, and the apparent displacement at the gray limestone aquifer level could be the result of differential rates of deposition caused by concurrent, deep-seated movement along the fault.

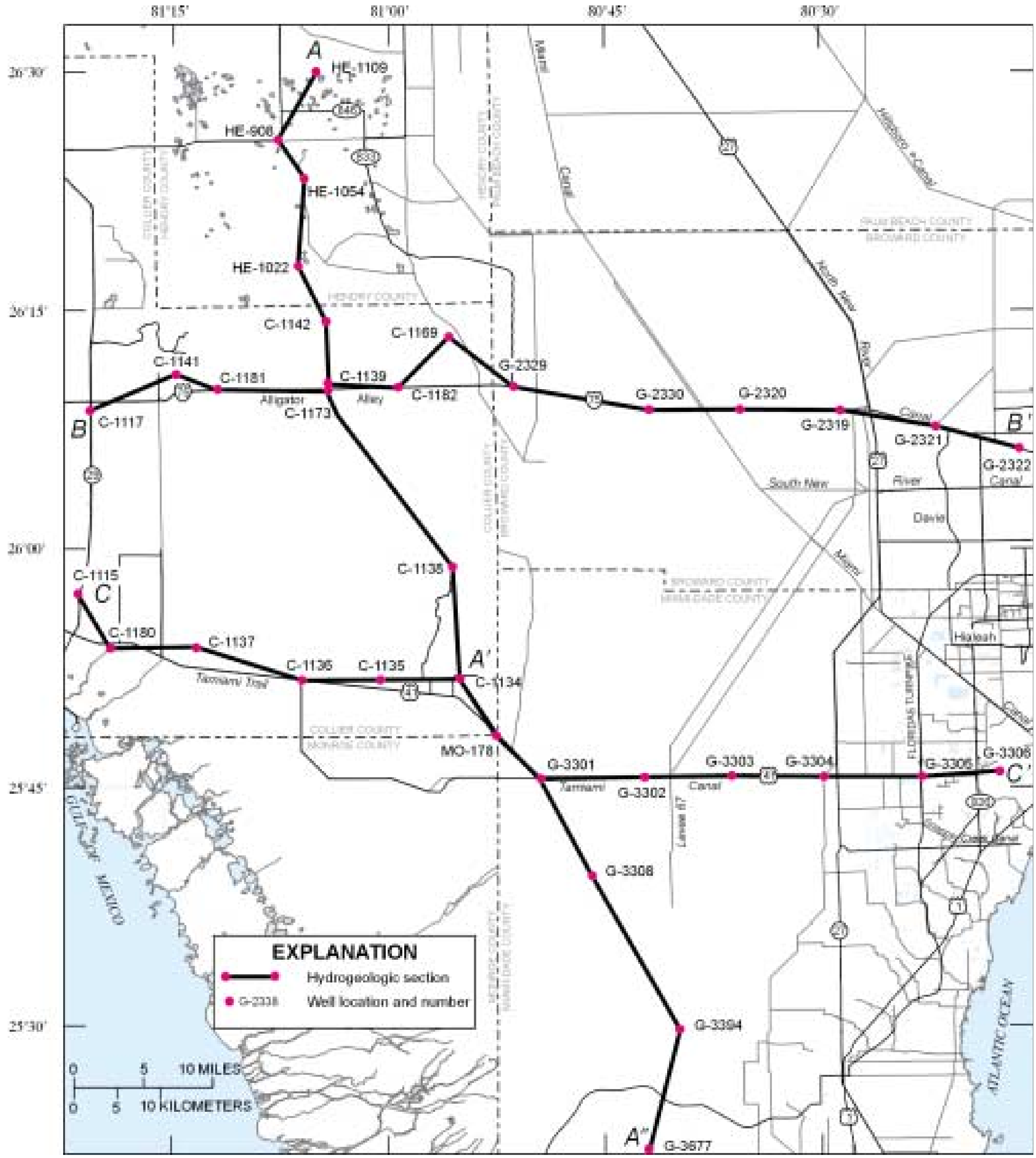
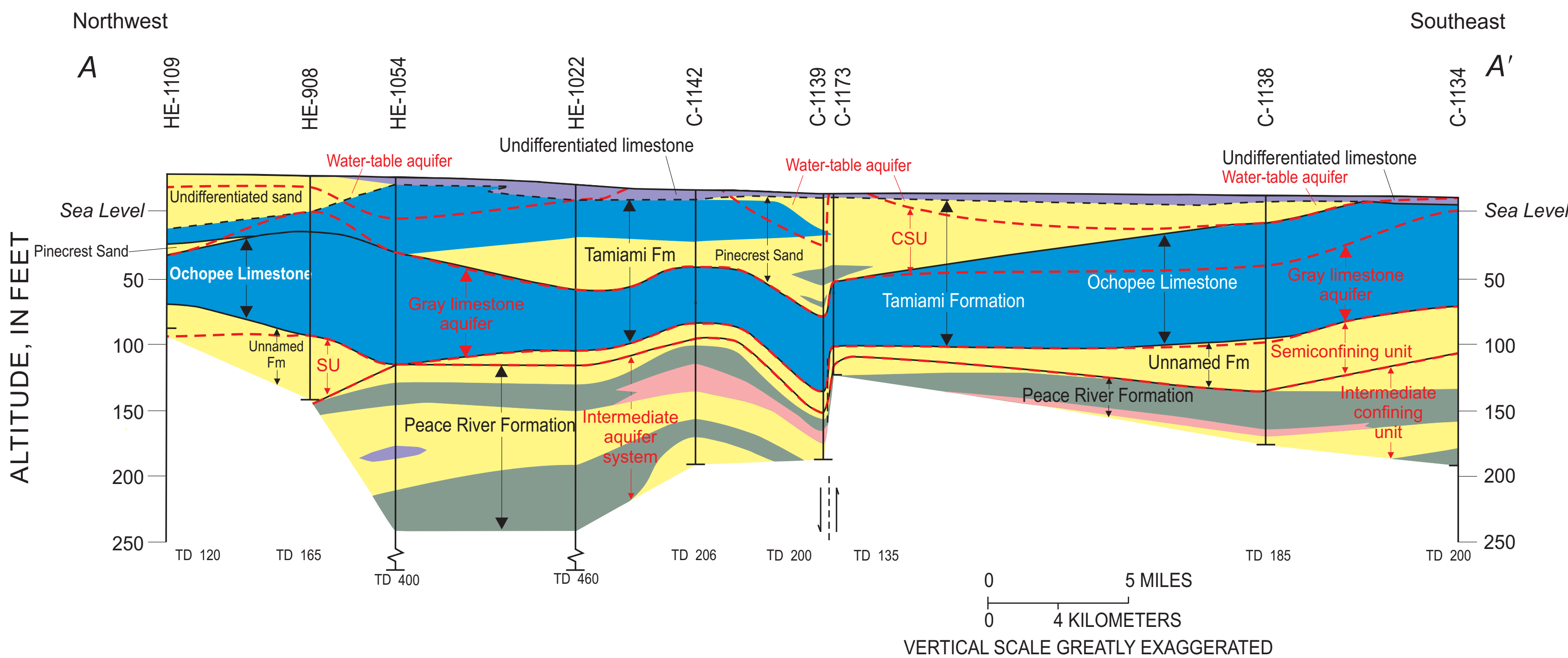


Figure 9. Traces of hydrogeologic section *A-A′*, *A′-A″*, *B-B′* and *C-C′* in the study area.



EXPLANATION

UNDIFFERENTIATED LIMESTONE

PELECYPOD RUDSTONE AND FLOATSTONE; MINOR PELECYPOD-RICH QUARTZ SAND OR SANDSTONE

QUARTZ SAND OR SANDSTONE

TERRIGENOUS MUDSTONE

DIATOMACEOUS MUDSTONE

HYDROSTRATIGRAPHIC BOUNDARY

LITHOSTRATIGRAPHIC BOUNDARY--Dashed where approximately located

POSTULATED FAULT--Direction of movement shown

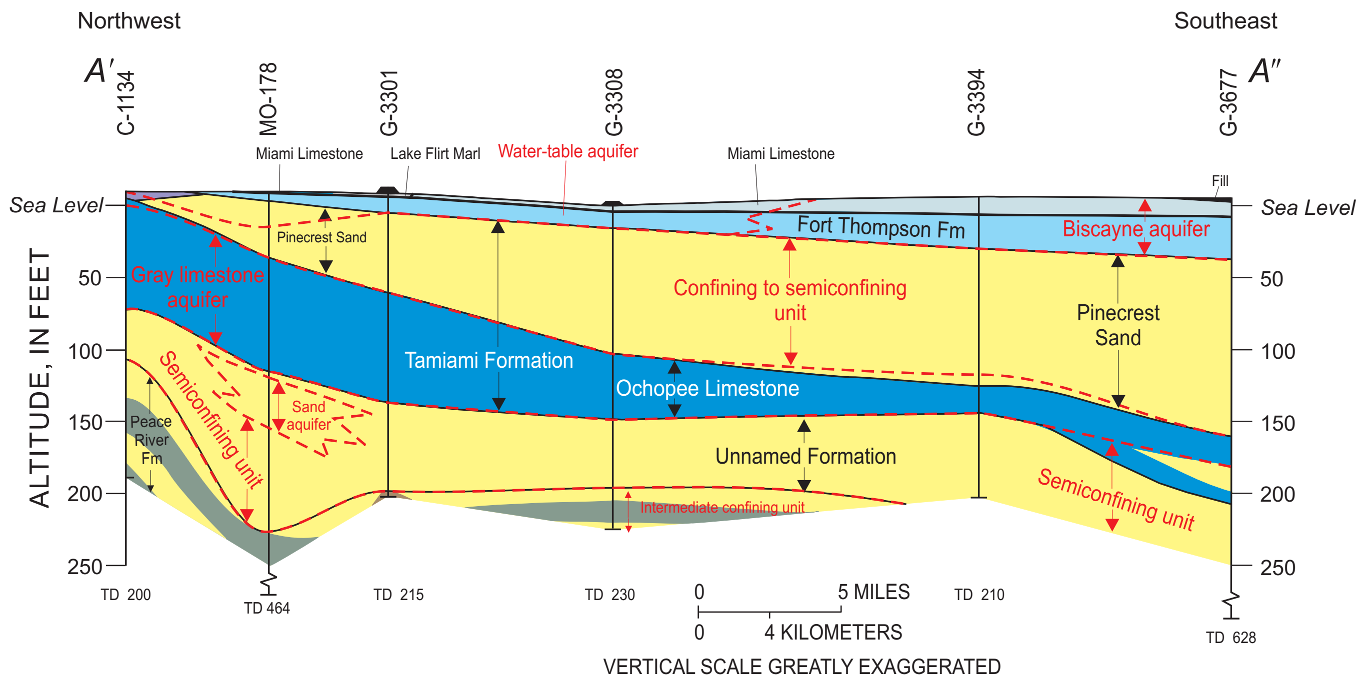
CSU CONFINING TO SEMICONFINING UNIT

SU SEMICONFINING UNIT

Fm FORMATION

TD TOTAL WELL DEPTH, IN FEET BELOW LAND SURFACE

Figure 10. Hydrogeologic section A-A′. Location of section line shown in figure 9.



EXPLANATION

(purple)	UNDIFFERENTIATED LIMESTONE
(light gray-blue)	OOLITIC LIMESTONE
(light blue)	PELECYPOD RUDSTONE AND FLOATSTONE; MINOR CALCRETE BEDS AND LAMINATIONS; LOCALLY *HELISOMA* FLOATSTONE
(blue)	PELECYPOD RUDSTONE AND FLOATSTONE; MINOR PELECYPOD-RICH QUARTZ SAND OR SANDSTONE
(yellow)	QUARTZ SAND OR SANDSTONE
(gray-green)	TERRIGENOUS MUDSTONE
– – – –	HYDROSTRATIGRAPHIC BOUNDARY
———	LITHOSTRATIGRAPHIC BOUNDARY
Fm	FORMATION
TD	TOTAL DEPTH, IN FEET BELOW LAND SURFACE

Figure 11. Hydrogeologic section A-A′. Location of section line shown in figure 9.

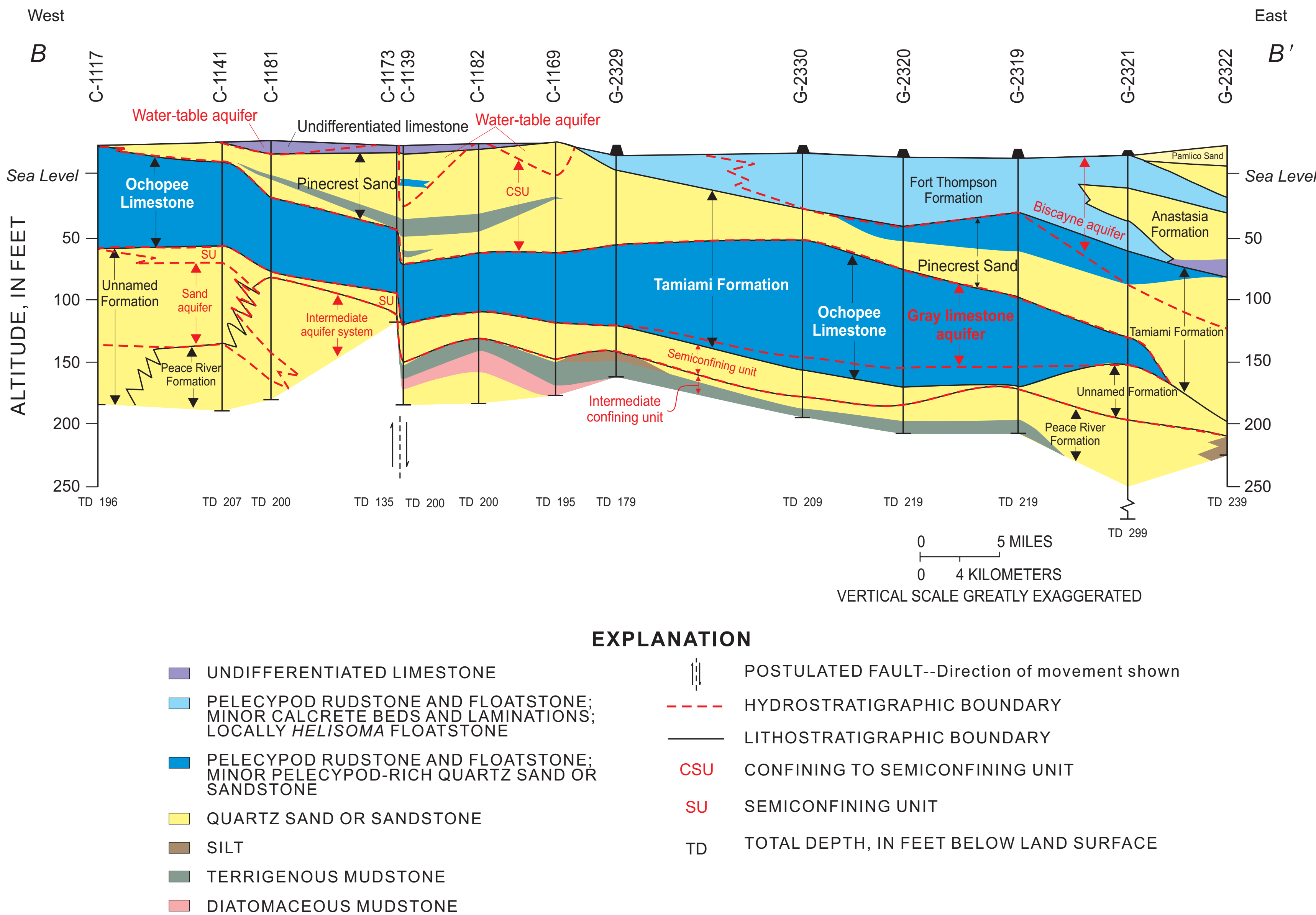


Figure 12. Hydrogeologic section *B-B′*. Location of section line shown in figure 9.

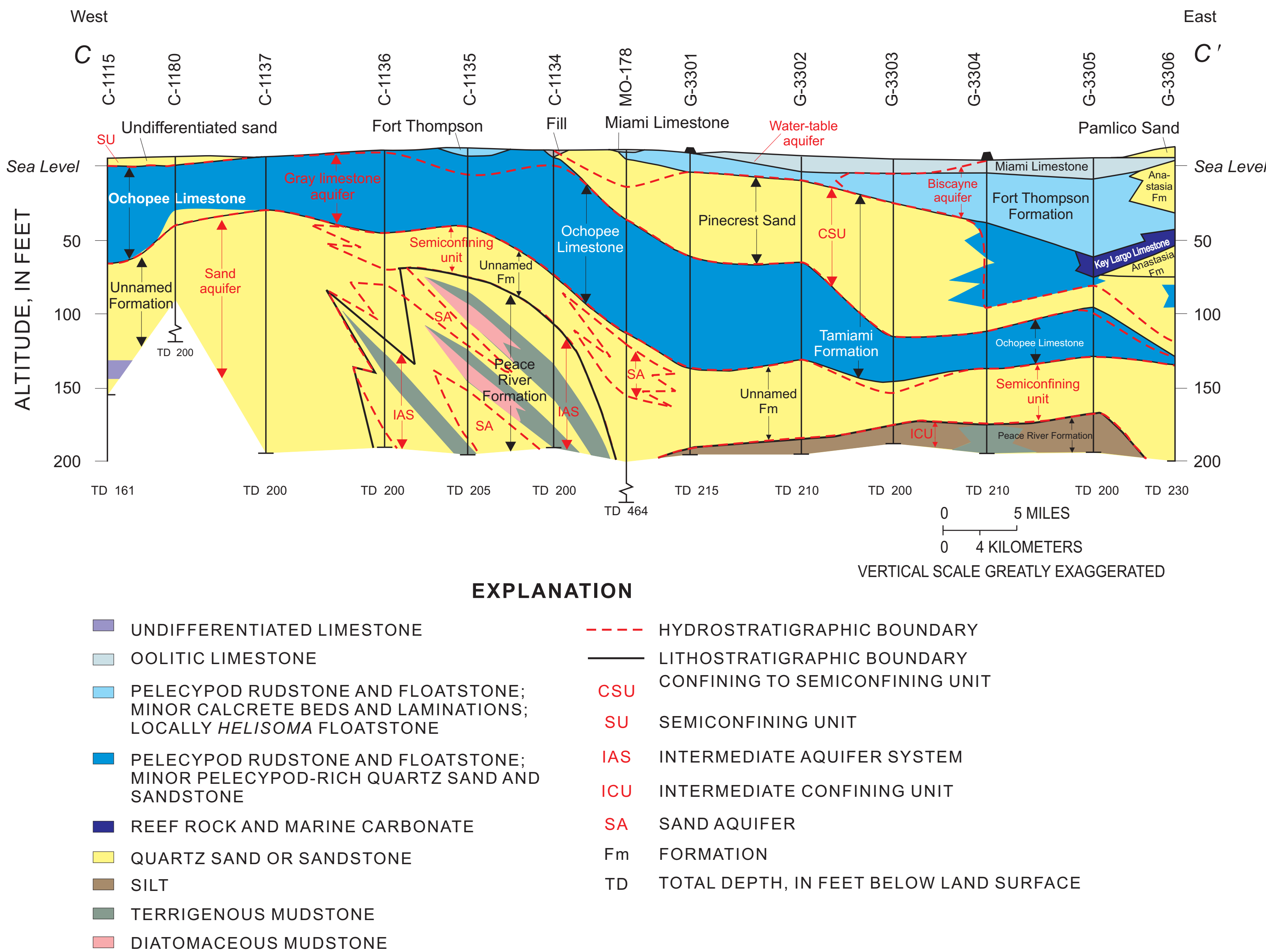
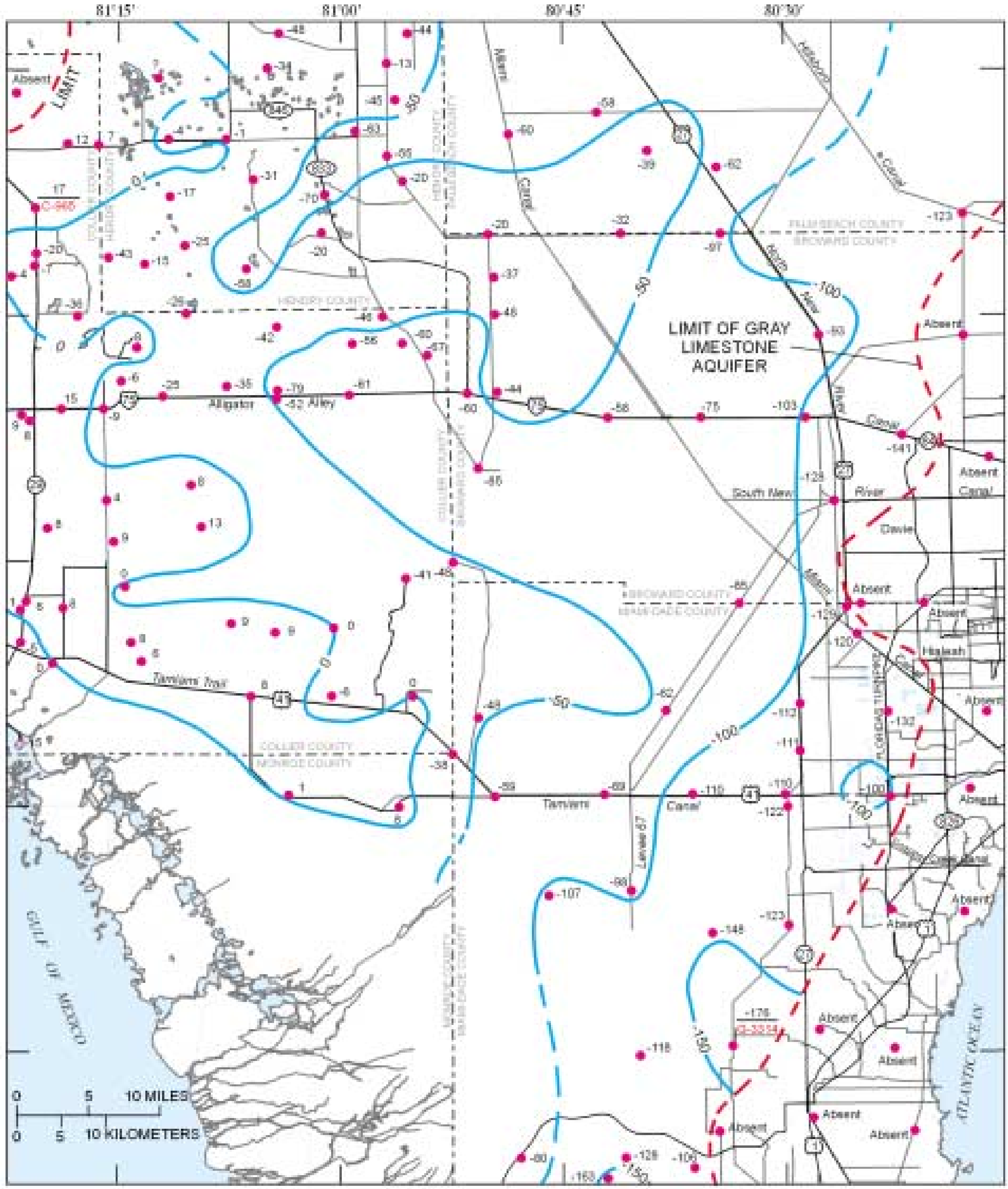


Figure 13. Hydrogeologic section *C-C′*. Location of section line shown in figure 9. Lithologies of test coreholes C-1134, C-1136, and MO-178 are based in part on descriptions from Weedman and others (1999).



— -50 — LINE OF EQUAL ALTITUDE–Shows altitude of the top of the gray limestone aquifer, in feet below (-) sea level. Interval is 50 feet. Dashed where approximately located

• -50 WELL LOCATION AND ALTITUDE–Number is altitude of the top of the gray limestone aquifer, in feet above or below (-) sea level. Question mark (?) indicates altitude is uncertain. Some well numbers are identified because they are mentioned in text. See figure 1 for all local well numbers

Figure 14. Altitude of the top of the gray limestone aquifer.

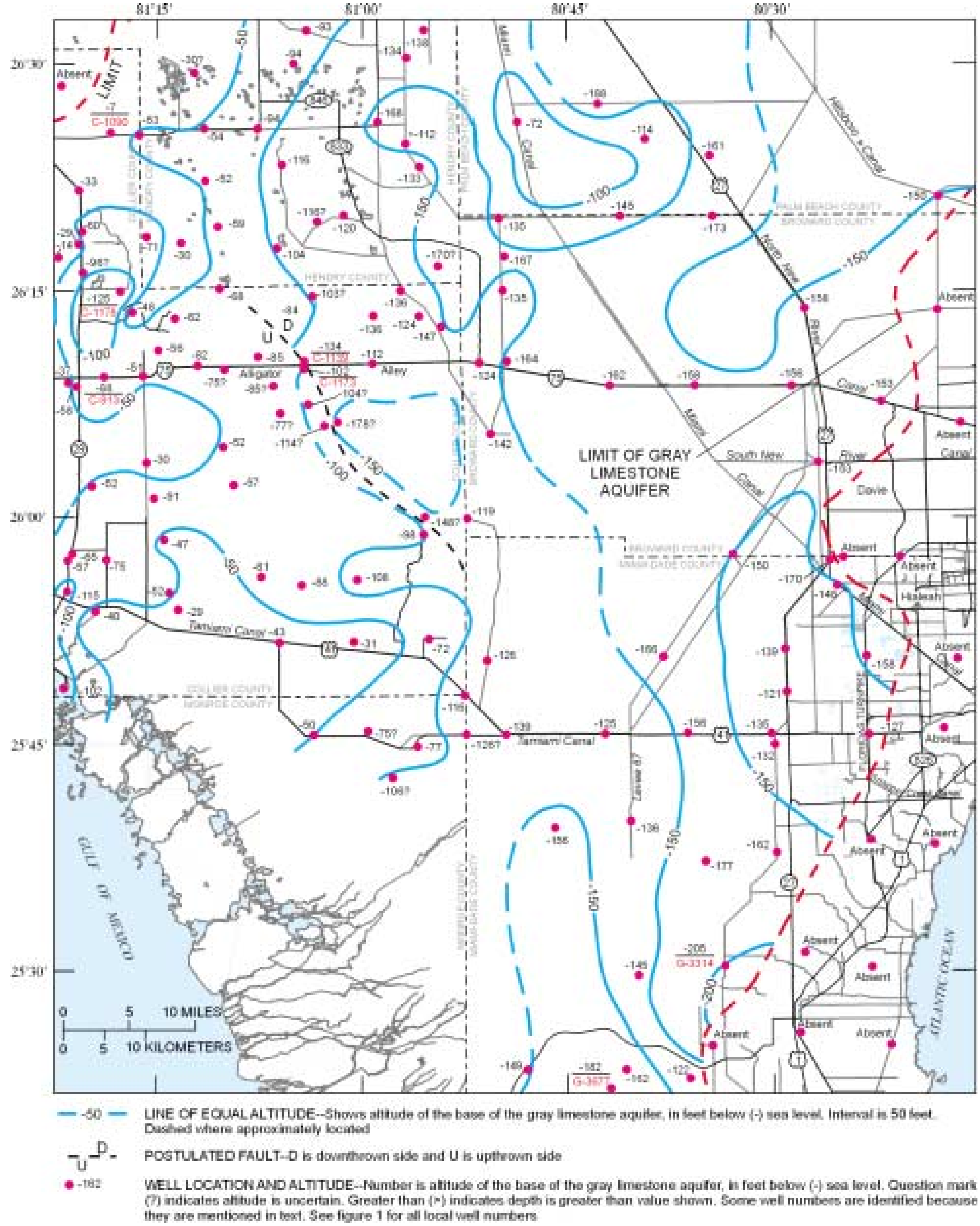


Figure 15. Altitude of the base of the gray limestone aquifer.

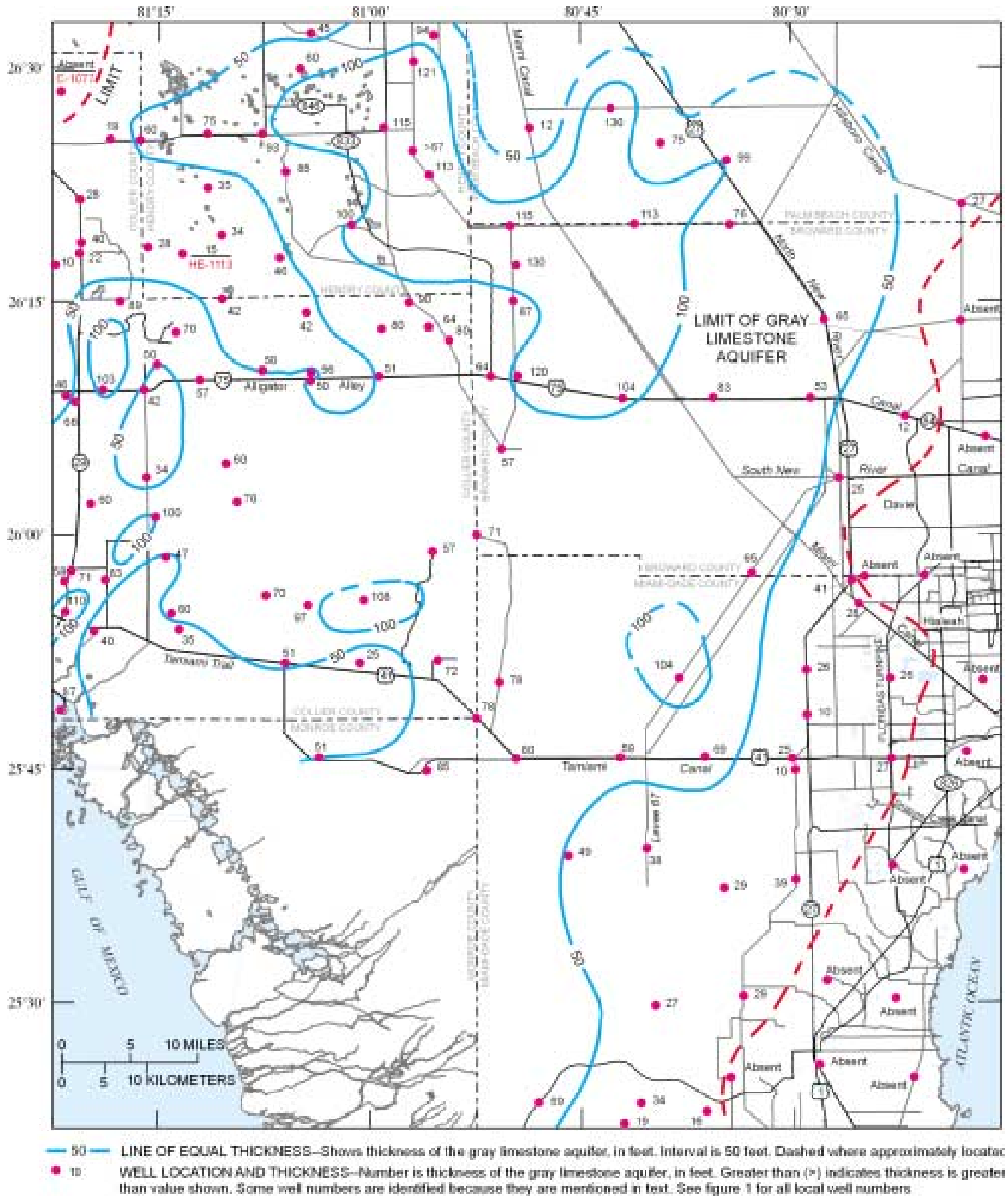


Figure 16. Thickness of the gray limestone aquifer.

Table 7. Tops of hydrogeologic units in selected wells as determined for this study

[Well locations shown in figure 1. All units shown in feet. Depths are from measuring point, which is at land surface or above. Type of data: 1, cuttings; 2, continuous core; 3, geophysical logs; and 4, reverse-air core. FGS, Florida Geological Survey; USGS, U.S. Geological Survey; DNP, did not penetrate; ?, questionable or uncertain depth, often because cuttings samples are of poor quality or are collected at large intervals; >greater than]

Local well identifier	Altitude of measuring point	Depth to top of upper confining or semi-confining unit	Depth to top of gray limestone aquifer	Depth to base of gray limestone aquifer	Type of data	Source of data
C-41	-5	?	20	107	1	USGS files
C-308	15	0	24	66	1	McCoy (1962)
C-701	34	?	?	130?	1	USGS files
C-791	38	?	30	90	1	USGS files
C-851	18	3	22	32	2	USGS files
C-873	37	?	?	140?	3	USGS files
C-913	15	Absent	0	103	1	Peacock (1983)
C-917	6	Absent	0	71	1	Peacock (1983)
C-918	8	Absent	0	83	1	Peacock (1983)
C-919	9	Absent	0	97	1	Peacock (1983)
C-920	9	Absent	0	70	1	Peacock (1983)
C-921	10	0	10	118	1	Peacock (1983)
C-922	8	Absent	0	70	1	Peacock (1983)
C-923	8	Absent	0	60	1	Peacock (1983)
C-927	8	Absent	0	60	1	Peacock (1983)
C-928	5?	0	10	120	1	Peacock (1983)
C-929	9	Absent	0	100	1	Peacock (1983)
C-930	15	10	50	100	1	Peacock (1983)
C-931	13	Absent	0	70	1	Peacock (1983)
C-965	21.96	0	5	55	1	Knapp and others (1986)
C-1074	26.71	0	20	80	1	Knapp and others (1986)
C-1077	30.64	Absent	Absent	Absent	1	Knapp and others (1986)
C-1090	25	4	13	32	2	FGS description
C-1091	13	Absent	4	50	2	FGS description
C-1115	5	Absent	4	62	2	Weedman and others (1997)
C-1117	13	Absent	5	71	2	Weedman and others (1997)
C-1125	36	?	?	150?	1	FGS-Fort Myers description
C-1126	40	?	?	115?	1	FGS-Fort Myers description
C-1128	38	?	?	115?	1	FGS-Fort Myers description
C-1133	38	?	?	142?	1	Current study
C-1134	10	0	10	82	2	Current study
C-1135	12	0	18	43	2	Current study
C-1136	10	Absent	2	53	2	Current study
C-1137	6	Absent	0	35	2	Current study
C-1138	11.4	20	52	109	2	Current study
C-1139	13	40	92	148	2	Current study
C-1140	8	2	9	55	2	Current study
C-1141	15	0	21	71	2	Current study
C-1142	16	0	58	100	2	Current study
C-1152	15	?	?	100?	1	Current study
C-1153	42	?	?	90	1	FGS-Fort Myers description
C-1154	20	0	40	80	1	Current study
C-1156	14	25	60	150	1	Current study
C-1157	14	50	70	150	1	Current study
C-1158	13	0	80	160	1	Current study
C-1159	12	?	?	190?	1	FGS description
C-1162	12	?	?	160?	1	Current study
C-1163	20	13	27	49	2	Cunningham and McNeil (1997)

Table 7. Tops of hydrogeologic units in selected wells as determined for this study (Continued)

[Well locations shown in figure 1. All units shown in feet. Depths are from measuring point, which is at land surface or above. Type of data: 1, cuttings; 2, continuous core; 3, geophysical logs; and 4, reverse-air core. FGS, Florida Geological Survey; USGS, U.S. Geological Survey; DNP, did not penetrate; ?, questionable or uncertain depth, often because cuttings samples are of poor quality or are collected at large intervals; >greater than]

Local well identifier	Altitude of measuring point	Depth to top of upper confining or semi-confining unit	Depth to top of gray limestone aquifer	Depth to base of gray limestone aquifer	Type of data	Source of data
C-1169	15	17	75	139	2	Current study
C-1173	13	0	65	115	2	Current study
C-1176	12	0	8	42	2	Current study
C-1178	19.2	3	55	144	2	Current study
C-1180	~5	0	6	45	2	Current study
C-1181	17	10	42	99	2	Current study
C-1182	13	0	74	125	2	Current study
C-1183	15	6	41	83	2	Current study
G-2296	15.5	?	60	180	1	USGS files
G-2311	~10	75	138	163	4	Fish (1988)
G-2312	~12	74	105	170	4	Fish (1988)
G-2313	~10	28	42	155	4	Fish (1988)
G-2314	~20	30	40	155	4	Fish (1988)
G-2315	~19	41	116	192	4	Fish (1988)
G-2316	~8	58	93	158	4	Fish (1988)
G-2317	~5	85	Absent	Absent	4	Fish (1988)
G-2318	~5	57	Absent	Absent	4	Fish (1988)
G-2319	~10	50	113	166	4	Fish (1988)
G-2320	~10	53	85	168	4	Fish (1988)
G-2321	~8	103	149	161	4	Fish (1988)
G-2322	~14	149	Absent	Absent	4	Fish (1988)
G-2329	~13	7	73	137	4	Fish (1988)
G-2330	~5	43	63	167	4	Fish (1988)
G-2338	~12	47	97	154	4	Fish (1988)
G-2340	~12	17	60	147	4	Fish (1988)
G-2341	~12	122	Absent	Absent	4	Fish (1988)
G-2346	~9	18	57	128	4	Fish (1988)
G-2891	13	30	50	180	1	FGS description
G-2912	~10	72	DNP	DNP	2	Current study
G-3238	14	?	?	140?	1	USGS files
G-3294	~9	117	138	179	4	Fish and Stewart (1991)
G-3295	~9	19	57	135	4	Fish and Stewart (1991)
G-3296	~8	43	70	174	4	Fish and Stewart (1991)
G-3297	~9	87	121	147	4	Fish and Stewart (1991)
G-3298	~8	99	140	166	4	Fish and Stewart (1991)
G-3299	~6	165	Absent	Absent	4	Fish and Stewart (1991)
G-3301	13	19	72	152	4	Fish and Stewart (1991)
G-3302	~6	14	79	138	4	Fish and Stewart (1991)
G-3303	~4	29	91	160	4	Fish and Stewart (1991)
G-3304	~9	102	119	144	4	Fish and Stewart (1991)
G-3305	~5	78	105	132	4	Fish and Stewart (1991)
G-3306	~12	127	Absent	Absent	4	Fish and Stewart (1991)
G-3308	~4	19	111	160	4	Fish and Stewart (1991)
G-3309	~2	16	100	138	4	Fish and Stewart (1991)
G-3310	~5	43	153	182	4	Fish and Stewart (1991)
G-3311	~12	51	135	174	4	Fish and Stewart (1991)
G-3312	~15	113	Absent	Absent	4	Fish and Stewart (1991)
G-3313	~15	123	Absent	Absent	4	Fish and Stewart (1991)
G-3314A	~5	56	181	210	4	Fish and Stewart (1991)

Table 7. Tops of hydrogeologic units in selected wells as determined for this study (Continued)

[Well locations shown in figure 1. All units shown in feet. Depths are from measuring point, which is at land surface or above. Type of data: 1, cuttings; 2, continuous core; 3, geophysical logs; and 4, reverse-air core. FGS, Florida Geological Survey; USGS, U.S. Geological Survey; DNP, did not penetrate; ?, questionable or uncertain depth, often because cuttings samples are of poor quality or are collected at large intervals; >greater than]

Local well identifier	Altitude of measuring point	Depth to top of upper confining or semi-confining unit	Depth to top of gray limestone aquifer	Depth to base of gray limestone aquifer	Type of data	Source of data
G-3315	~15	97	175	180	4	Fish and Stewart (1991)
G-3316	~12	95	Absent	Absent	4	Fish and Stewart (1991)
G-3317	~4	27	84	153	4	Fish and Stewart (1991)
G-3318	~4	43	132	166	4	Fish and Stewart (1991)
G-3319	~3	33	166	170	4	Fish and Stewart (1991)
G-3320	~9	87	Absent	Absent	4	Fish and Stewart (1991)
G-3321	~6	111	Absent	Absent	4	Fish and Stewart (1991)
G-3394	~6	36	124	151	4	Fish and Stewart (1991)
G-3671	~6	105	128	138	2	Current study
G-3673	~15	96	126	136	2	Current study
G-3674	~5	90	125	153	2	Current study
G-3675	~5	75	DNP	DNP	2	Current study
G-3677	~4	43	167	186	2	McNeill and others (1996)
HE-591	15	20	60	DNP	1	Smith and Adams (1988)
HE-868	25	30	95	DNP	1	Smith and Adams (1988)
HE-901	26	10	30	80	1	Smith and Adams (1988)
HE-902	22	30	85	190	1	Smith and Adams (1988)
HE-908	24	6	25	118	1	Smith and Adams (1988)
HE-976	38	?	?	154?	3	USGS files
HE-1016	23	10	40	75	1	Smith and Adams (1988)
HE-1021	20	5	40	140	1	Smith and Adams (1988)
HE-1022	20	12	78	124	1	Smith and Adams (1988)
HE-1037	27	35	75	120	1	Smith and Adams (1988)
HE-1054	24	30	55	140	1	Smith and Adams (1988)
HE-1075	18	3	62	156	1	Smith and Adams (1988)
HE-1089	30	?	?	60?	1	Current study
HE-1101	30	?	?	200?	3	USGS files
HE-1108	20	25	75	>132	1	Smith and Adams (1988)
HE-1109	26	9	60	120	1	Smith and Adams (1988)
HE-1110	15	0	35	148	4	Current study
HE-1112	21	Absent	46	80	2	Current study
HE-1113	20	12	35	50	2	Current study
HE-1114	20	16	63	91	2	Current study
HE-1115	32	4	100?	123	2	Current study
HE-1116	18	11	31	152	2	Current study
MO-138	14	Absent?	?	120?	1	Current study
MO-141	25	?	?	100?	3	USGS files
MO-177	8	Absent	0	78	2	Current study
MO-178	10	25	48	126	2	Current study
MO-179	6	Absent	5	56	2	Current study
NP-100	4.5	58	110	126	1	USGS files
PB-1428	12	119	135	162	4	Fish and others (1988)
PB-1485	10	?	68	198	1	Miller (1987)
PB-1696	11	0	50	125	1	Current study
PB-1703	20	19	80	92	2	Current study
PB-1704	11	3	73	173	2	Current study

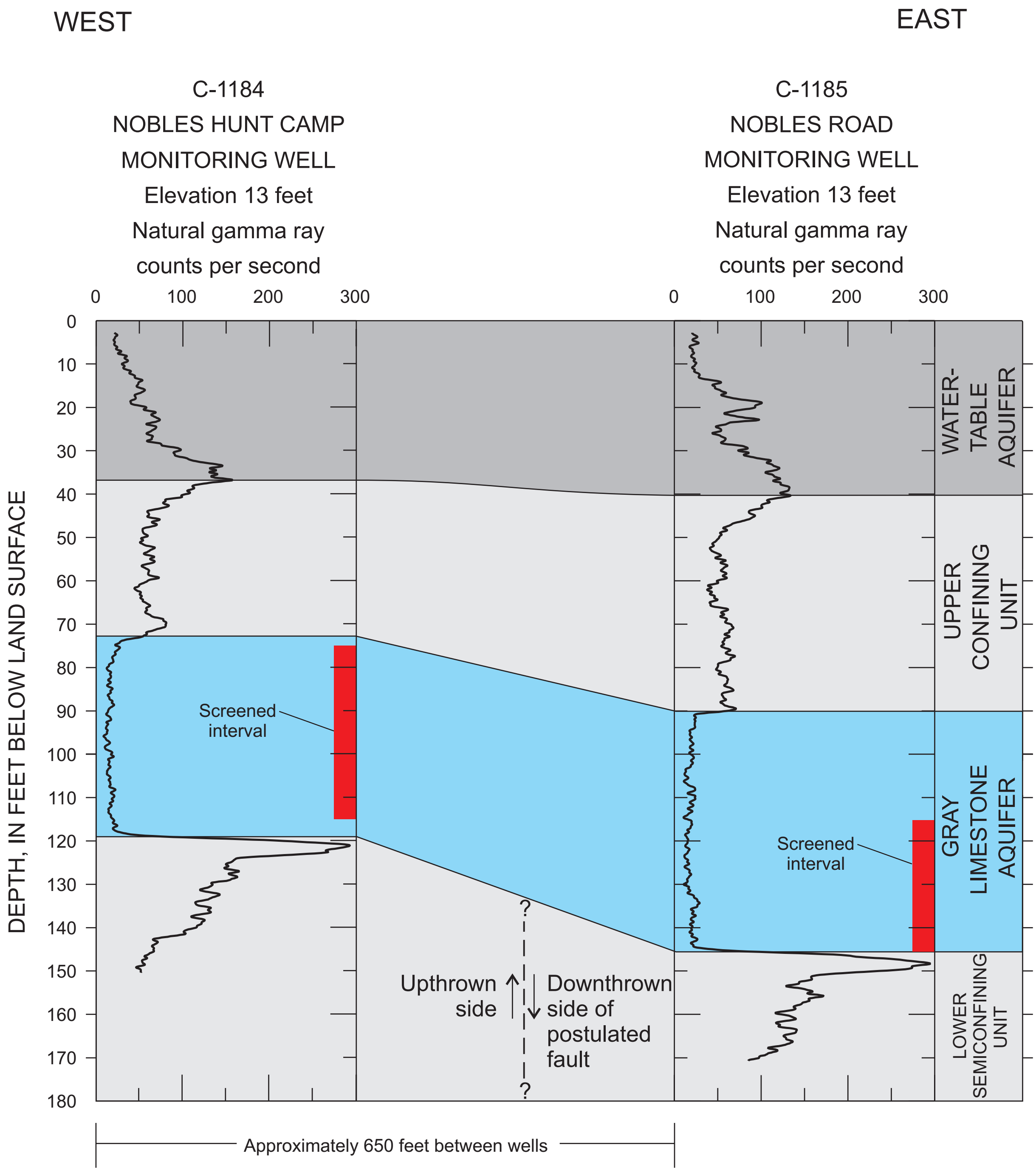


Figure 17. Hydrogeologic section showing correlation between wells C-1184 and C-1185 in eastern Collier County using gamma-ray logs. Well C-1185 is located 60 feet west of test corehole C-1139 at the Noble's Road site (see figure 1).

Evidence for a similar southeast fault trend has been observed in eastern Lee and northwestern Collier Counties, as indicated by possible displacement of a lower Arcadia Formation marker unit (Reese, 1999, fig. 6). The axis of a narrow structural depression mapped in this previous study can be projected to the southeast to approximately align with the postulated fault in northeastern Collier County (fig. 15).

The gray limestone aquifer and its confining unit were mapped in the portion of the study area in central and eastern Collier County and southern Hendry County (Shoemaker, 1998). The purpose of Shoemaker's study was to better define these units using surface geophysics in areas inaccessible to drilling or where well control was sparse. A total of 65 time-domain electromagnetic (TDEM) and 33 direct-current (DC) resistivity soundings were completed in the vicinity of, or along, transects between test wells drilled during this study as well as previous studies. These soundings provided information on the thickness and depth to geoelectric layers within the study area, and a comparison of geoelectric and hydrogeologic units at eight well locations suggested major contrasts in electrical resistivity are coincident with contacts between hydrogeologic units. Based on this comparison, it was assumed that geoelectric layers correspond to hydrogeologic units, and the hydrogeologic units were mapped using the TDEM and DC data in addition to data collected from 12 test wells.

Some of the surface-geophysical data were collected close to the projected position of the postulated fault in northeastern Collier County (fig. 15), and evidence for displacement of the base of the gray limestone aquifer across the fault was not found. However, in general, significant variability in estimates of the depth to the base of the gray limestone aquifer was found to be present over short distances. Potential sources of this variability include a complex hydrogeologic framework, poor correspondence between geoelectric and hydrogeologic units, poor resolution of the depth to the base of the gray limestone aquifer by surface-geophysical soundings, or cultural noise that was undetected (Shoemaker, 1998).

HYDROGEOLOGIC FRAMEWORK OF SOUTHERN FLORIDA

Southern Florida is underlain by aquifer systems that include the regionally extensive surficial and Floridan aquifer systems (Miller, 1986). In southwestern Florida, the intermediate aquifer system separates these two regional aquifer systems and contains aquifers that are sandwiched between thick confining units (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). To the east, these aquifers of the intermediate aquifer system either pinch out or grade out by facies change, and only the intermediate confining unit is present in southeastern Florida. The intermediate confining unit is equivalent to the upper confining unit of the Floridan aquifer system (Miller, 1986). The relations between the hydrologic nomenclatural scheme proposed herein and those in other studies is presented in figure 18.

Surficial Aquifer System

The surficial aquifer system includes all rocks and sediments from land surface to the top of the intermediate confining unit or intermediate aquifer system. Its lower limit "coincides with the top of laterally extensive and vertically persistent beds of much lower permeability" (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). The surficial aquifer system in southern Florida consists mostly of beds of limestone, unconsolidated quartz sand, terrigenous mudstone, shell, and quartz sandstone. Limestone beds constitute the major component of two aquifers: the Biscayne aquifer and gray limestone aquifer. These aquifers can grade into one another and into a third aquifer, the water-table aquifer, which occurs to the west and north of the Biscayne aquifer (fig. 18).

The water-table aquifer extends from land surface to the top of confining beds that are part of the upper Tamiami Formation, or the aquifer merges with the top of the gray limestone aquifer. In much of the study area, the water-table aquifer comprises near-surface undifferentiated quartz sand and limestone or quartz sand and limestone of the Pinecrest Sand that merge laterally to the east with the Biscayne aquifer. In most of Monroe County and south-central and western Collier County, the gray limestone aquifer is the water-table aquifer; in this area the water-table aquifer has also been referred to as the Chokoloskee aquifer (Jarosewich and Wagner, 1985).

The Biscayne aquifer was named and defined by Parker (1951, p. 820) and is the only formally named aquifer contained within the surficial aquifer system. The Biscayne is the principal aquifer and a sole-source aquifer (Federal Register Notice, 1979) in southeastern Florida. It is the most productive aquifer of the surficial aquifer system and one of the most permeable water-bearing units in the world (Parker and others, 1955).

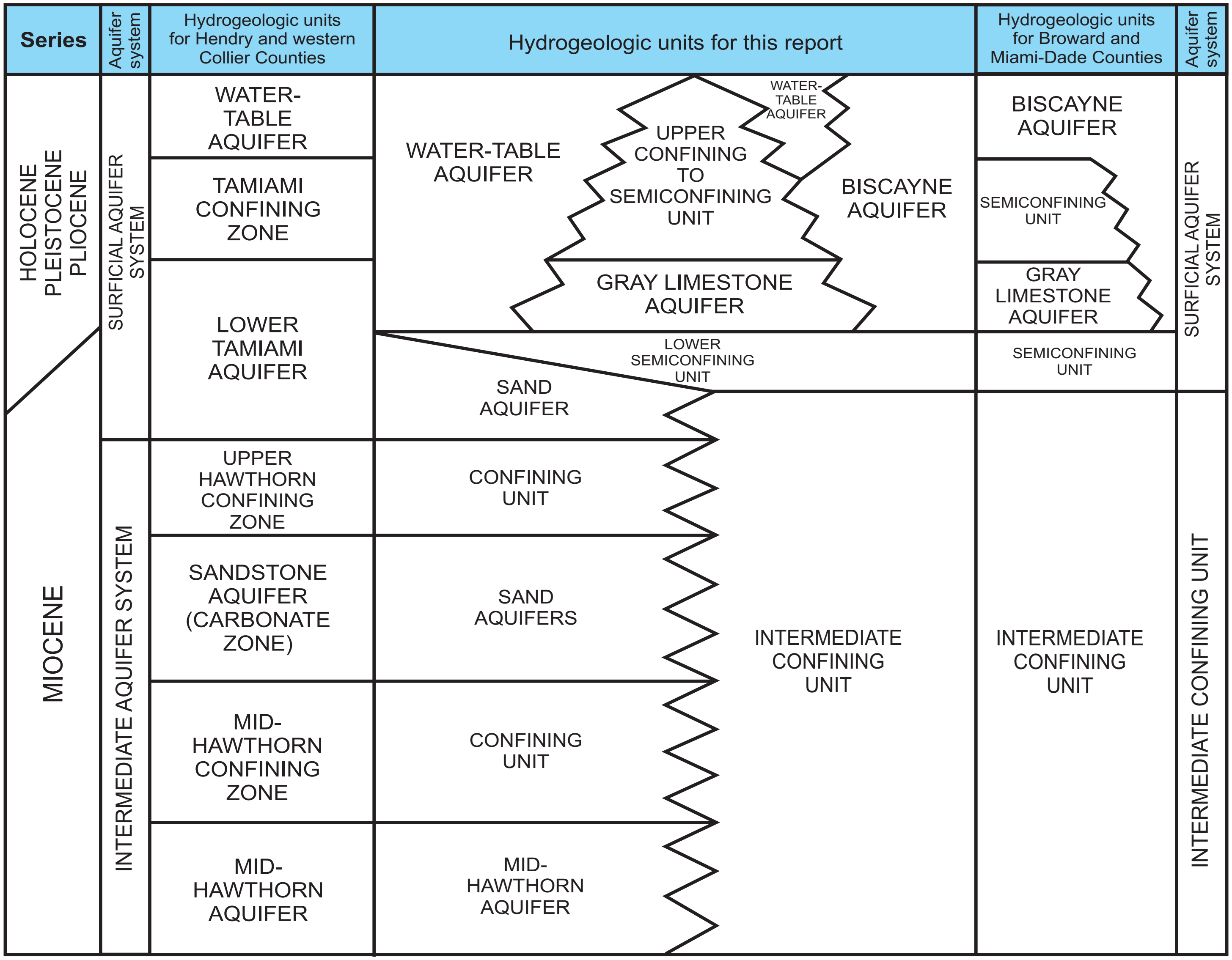


Figure 18. Hydrogeologic nomenclature used in previous studies and in this report. Nomenclatures are shown in a generally west-to-east order. Hendry County nomenclature by Smith and Adams (1988), western Collier County nomenclature by Knapp and others (1986), Miami-Dade County nomenclature by Fish and Stewart (1991), and Broward County nomenclature by Fish (1988).

Fish (1988, p. 20) defined the Biscayne aquifer as:

> "That part of the surficial aquifer system in southeastern Florida comprised (from land surface downward) of the Pamlico Sand, Miami Oolite (Limestone), Anastasia Formation, Key Largo Limestone, and Fort Thompson Formation all of Pleistocene age, and contiguous highly permeable beds of the Tamiami Formation of Pliocene age, where at least 10 ft of the section is highly permeable (a horizontal hydraulic conductivity of about 1,000 ft/d or more)."

For Miami-Dade (Fish and Stewart, 1991) and Broward (Fish, 1988) Counties, the permeability requisite of this definition provides an approach for estimating the boundary of the Biscayne aquifer.

Intermediate Aquifer System and Intermediate Confining Unit

In this report, the intermediate aquifer system is defined as those aquifers that lie below the top of the Peace River Formation. This definition is consistent with Fish's (1988) and Fish and Stewart's (1991) inclusion of limestones of the Tamiami Formation in the surficial aquifer system in Broward and Miami-Dade Counties. However, this definition differs from Miller's (1990) delineation of the intermediate aquifer system in southwestern Florida, which includes sand, limestone, and shell beds of the Tamiami Formation.

Water-yielding rocks of the intermediate aquifer system are known to be widely present only in the northwestern part of the study area in Hendry and western Collier Counties (Smith and Adams, 1988). Locally, quartz sand aquifers occur within the Peace River Formation in the study area; for example, in well C-1135 (fig. 13). However, the lateral extent of these aquifers in the study area is poorly understood.

HYDROGEOLOGY OF THE GRAY LIMESTONE AQUIFER

The gray limestone aquifer includes the Ochopee Limestone Member of the Tamiami Formation and, in some areas, a small portion of the underlying unnamed formation (fig. 4). Although the gray limestone aquifer is well confined in some areas, it is placed in the surficial aquifer system in this study, as it has been in previous studies (Fish, 1988; Fish and Stewart, 1991). Discussion of the gray limestone aquifer in this section includes its definitions, delineation of the thickness and extent of the aquifer and its confining units, description of its pore system geometry based on core study, determination of the hydraulic properties and porosity of the aquifer, and delineation of the distribution of these hydraulic properties and the degree of confinement of the aquifer. Measurements of water level and water quality in the gray limestone aquifer are used to gain an understanding of the ground-water flow system of the aquifer.

The gray limestone aquifer was defined by Fish (1988) as follows:

> "That part of the limestone beds (usually gray) and contiguous, very coarse, clastic beds of the lower to middle part of the Tamiami Formation that are highly permeable (having a hydraulic conductivity of about 100 ft/d or greater) and at least 10 ft thick."

In this report, the gray limestone aquifer was mapped according to hydraulic conductivity criteria that slightly differ from that of Fish (1988). Limestone and sandstone of the Ochopee were included in the gray limestone aquifer if hydraulic conductivities were moderate to very high (about 10 ft/d or greater). Quartz sand and sandstone of the unnamed formation contiguous to limestone beds at the base of the Ochopee were included in the gray limestone aquifer if hydraulic conductivity was high to very high (about 100 ft/d or greater) or included moldic porosity. In this study, hydraulic conductivity assessment is based on core samples, core analyses, aquifer tests, and flowmeter log results. The data assembled by Fish (1988) and Fish and Stewart (1991) for Broward and Miami-Dade Counties, respectively, were reevaluated, resulting in only minor changes.

The gray limestone aquifer is the same as the lower Tamiami aquifer in southern Hendry County (fig. 18). This equivalency is shown by hydrogeologic sections A-A′ and B-B′ (figs. 10 and 12). To the west and south in Collier and Monroe Counties, the aquifer becomes the water-table or Chokoloskee aquifer and is probably hydraulically continuous with the upper predominantly limestone part of the lower Tamiami aquifer of Knapp and others (1986) (figs. 12, 13, 18 and 19).

Characteristic borehole geophysical log responses in the gray limestone aquifer in an area where it is semiconfined to confined are shown in well C-1183 in eastern Collier County (figs. 1 and 20). Borehole log responses shown are induction resistivity, natural gamma ray, spontaneous potential, and single-point resistance. The gray limestone aquifer, as in most of the study area, is best defined by the natural gamma-ray curve; it has a gamma-ray activity that is much lower than that in the upper and lower confining units.

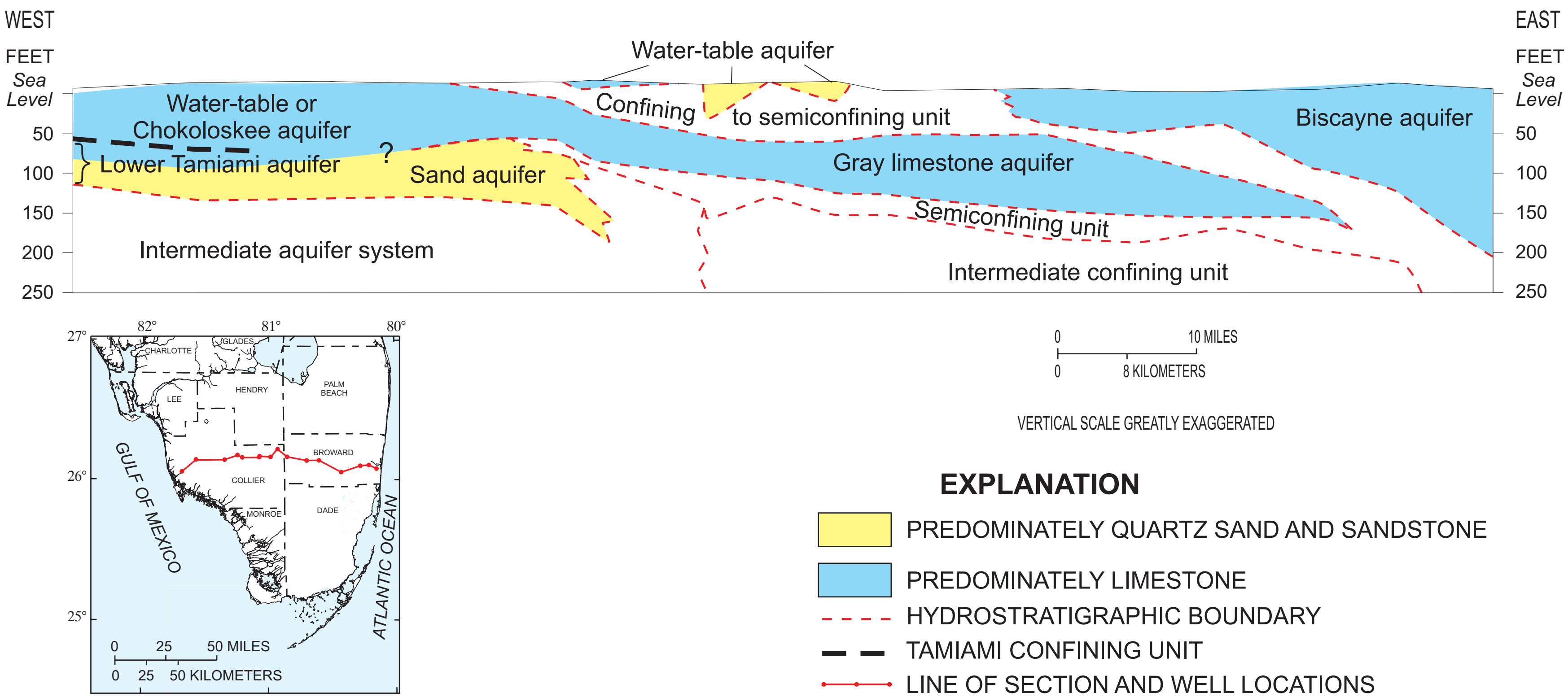


Figure 19. Relations among aquifers and confining units in a coast-to-coast section across the southern peninsula of Florida along Alligator Alley. Section line drawn, from west to east, through the Southern States Utilities and Picayune Strand test wells (Weedman and others, 1997), wells C-1117, C-1141, C-1181, C-1173, C-1139, C-1182, C-1169, G-2329, G-2330, G-2320, G-2319, G-2321, G-2322 (all listed in appendix II), and G-2345 and G-2347 (both listed in Fish, 1988).

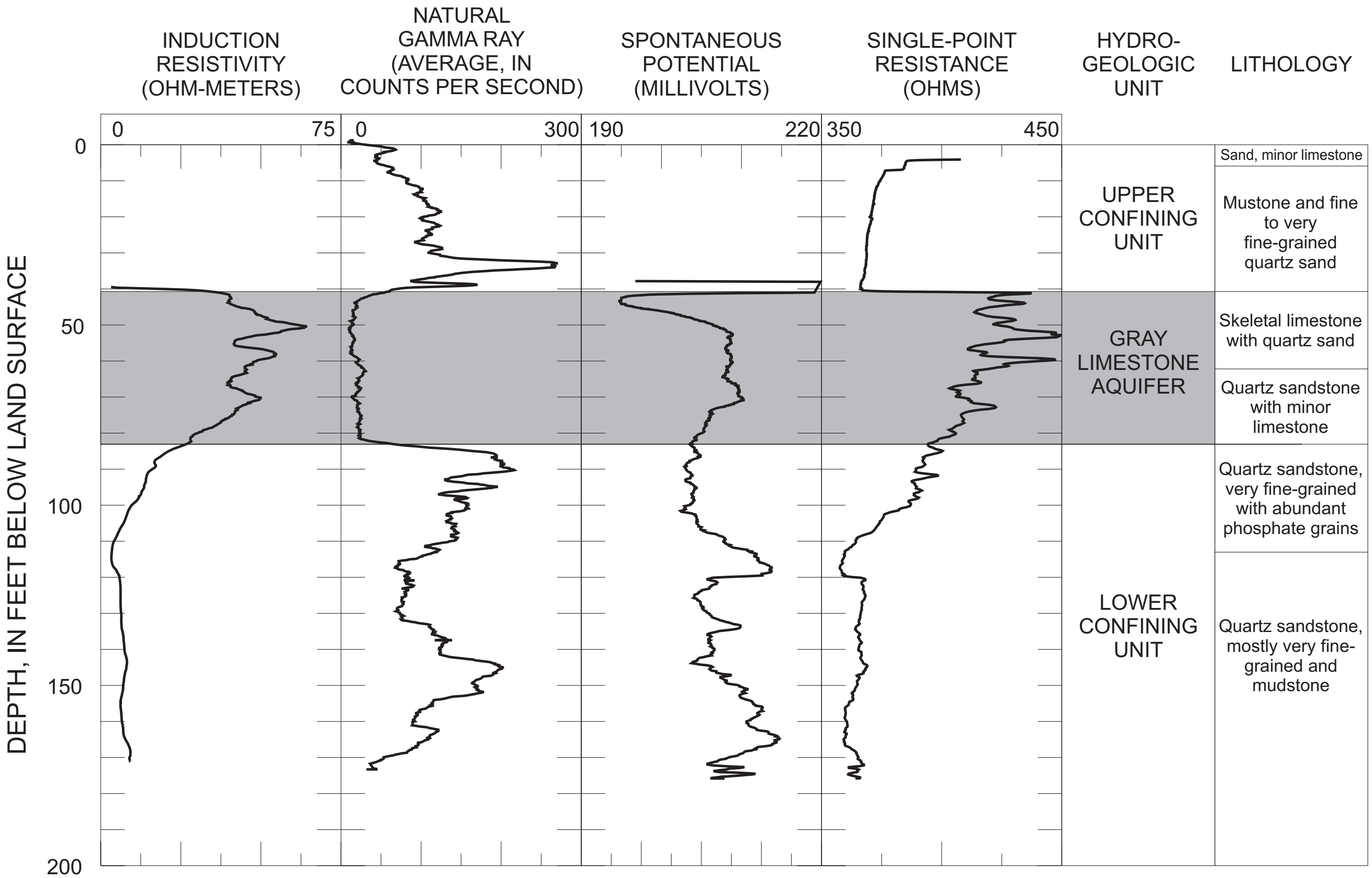


Figure 20. Geophysical logs, hydrogeologic units, and lithology of test well C-1183 at Baker's Grade site in eastern Collier County. Steel casing extended to 41 feet below land surface during geophysical logging.

Configuration, Thickness and Extent of the Aquifer and Its Confining Units

The geometry, thickness, and physical extent of hydrogeologic units were delineated on the basis of lithologic and borehole geophysical data, well-to-well correlation, core sample analysis, an evaluation of available flowmeter log data, and aquifer test results. The configuration, extent, and thickness of various water-bearing and confining units may not necessarily correspond to geologic units that underlie this area. Rather, a comparison of the relative change in permeability between adjoining rock units and their lithofacies played an integral part in helping to define and delineate major aquifers and confining units. Hydrogeologic and lithostratigraphic units are shown on the hydrogeologic sections (figs. 10-13).

The top and base of the gray limestone aquifer are similar in that both surfaces are shallowest in Collier and Hendry Counties and slope to the southeast and east (figs. 14 and 15). The altitude of the top of the gray limestone aquifer generally ranges between sea level and 100 ft below sea level in the study area. However, it is as much as 17 ft above sea level in northwestern Collier County (fig. 14, well C-965) and as low as 176 ft below sea level in south-central Miami-Dade County (fig. 14, well G-3314). The altitude of the base of the aquifer generally ranges from 50 to 160 ft below sea level, but the basal surface can be comparatively irregular in some areas. This is apparent in northwestern to central Collier County where the base of the aquifer is as shallow as 7 ft below sea level in well C-1090 and extends to a depth of 125 ft below sea level in well C-1178 (fig. 15). The base of the aquifer lies at a maximum depth of 205 ft below sea level in southeastern Miami-Dade County (fig. 15, well G-3314). An irregularly shaped anticline on the top of the gray limestone aquifer extends across southwestern Palm Beach, northwestern Broward, and southern Hendry Counties with an altitude as high as 20 ft below sea level. On the base of the aquifer, a syncline is present in some of the same area occupied by this anticline.

The thickness of the gray limestone aquifer generally ranges from 30 to 100 ft (fig. 16). The thickness of the unnamed formation included within the aquifer at its base ranges from 1 to 20 ft in seven test wells where it is present (appendix II). The aquifer is thickest in southwestern Palm Beach, northwestern Broward, and southern Hendry Counties where it ranges from 100 to as much as 130 ft thick. Local areas of similar thickness are found in western and southeastern Collier County and northern Miami-Dade County. Many of the areas where the aquifer is thick correspond to where the altitude of the base of the aquifer is low, such as in southern Hendry County, northwestern Broward County, and parts of western Collier County (figs. 15 and 16).

The northern and western extents of the gray limestone aquifer were not defined in this study. Although the aquifer is interpreted to be absent in well C-1077 in northwestern Collier County (fig. 16), the lower Tamiami aquifer is mapped as being present in most of western and northeastern Hendry County (Smith and Adams, 1988, fig. 21), which are outside of the study area. However, the limestones of the Tamiami Formation, which are included in the lower Tamiami aquifer, thin to the north, and sand and sandstone layers make up most of the thickness of the formation in central Hendry County (Smith and Adams, 1988, p. 10).

The easternmost extent of the gray limestone aquifer corresponds closely to the limits previously delineated by Fish (1988) and Fish and Stewart (1991). In northeastern Broward County, the eastern edge of the aquifer occurs at the transition from highly permeable limestone or contiguous shell sand to a significantly less permeable facies composed of sandy, clayey limestone and quartz sand and sandstone. In northeastern Miami-Dade County, the eastern limit of the aquifer is mapped where the aquifer merges with the Biscayne aquifer and the intervening semiconfining unit wedges out. South of the Tamiami Trail, the eastern boundary occurs at a transition to less-permeable siliciclastic sediments.

The gray limestone aquifer is overlain and underlain by upper and lower confining to semiconfining units in most of the study area. These units are usually composed of siliciclastics of low to very low hydraulic conductivity (sand, clayey sand, mudstone, and clay), but they can also be principally limestone of low hydraulic conductivity (figs. 10-13). As described earlier in this report, rock lithofacies and their interpreted hydraulic properties served as important factors in delineation of water-bearing and less-permeable hydrogeologic units.

The term “confining unit” is often used in a general sense in this report. The presence of confining units bounding the gray limestone aquifer does not necessarily imply confining conditions, rather that the aquifer is bounded by lithologic units that are less permeable than the aquifer as determined by visual estimation, core analysis, or aquifer testing. Terms used herein to further qualify the degree of confinement provided by a confining unit are "semiconfining unit" and "good confining unit." The term "semiconfining" indicates a range in confinement from poor to moderate. As described later in this report, the gray limestone aquifer can be bounded above by what is described as a semiconfining unit, yet characteristics of the response of the aquifer to an aquifer test can indicate unconfined conditions. The terms "good confinement" or "well confined" are based on leakance as determined from aquifer testing, and they are defined using this property later in the report. Leakance is related to the thickness and vertical hydraulic conductivity of a confining unit.

Contour maps that delineate the top and thickness of the confining unit bounding the top of the gray limestone aquifer are shown in figures 21 and 22. The altitude of the top of the confining unit ranges from 10 ft above sea level to 50 ft below sea level in much of the study area, and this surface slopes downward to the east and to the southeast (fig. 21). The areas of lowest altitude of the top of the confining unit are in eastern Palm Beach and Broward Counties and in eastern and south-central Dade County where the altitude ranges from 50 to 108 ft below sea level. These areas adjoin and are close to the eastern limit of the gray limestone aquifer.

The upper confining unit ranges from 20 to 60 ft in thickness in most of the study area, but is absent to the west and southwest in much of Collier County and most of Monroe County (fig. 22). The confining unit is thickest in south-central and southwestern Miami-Dade County, where the unit is as much as 125 ft thick in well G-3314 (fig. 22). This area corresponds, in part, to areas of low structural altitude of the top of the gray limestone aquifer (fig. 14). The unit thickens to 50 ft or more in an area that extends southeastward from southern Hendry County through northeastern Collier County and into western Broward County. This area also generally corresponds to an area of low altitude of the top of the gray limestone aquifer. The confining unit also thickens to 50 ft or more in southern Palm Beach County and north-central and central Broward County. Local thickening occurs in west-central Collier County in well C-1178 (fig. 22) and corresponds to an area where the gray limestone aquifer also thickens. The upper confining unit is thin in an area that includes small contiguous parts of southwestern Palm Beach, northeastern Broward, and southern Hendry Counties, and in this area the underlying gray limestone aquifer is both thick and its upper surface is elevated. In southeastern Hendry County, the upper confining unit is locally absent (fig. 22, well HE-1112); quartz sand deposits equivalent to the upper confining unit here have moderate hydraulic conductivity.

A semiconfining unit is present below the gray limestone aquifer in most of the study area (figs. 10-13). However, except for parts of Collier County in the western part of the study area, the base of this semiconfining unit marks the base of the surficial aquifer system; it is underlain by silt and mudstone confining beds of very low hydraulic conductivity contained in the intermediate aquifer system or the intermediate confining unit.

Controls on Porosity and Permeability

Porosity in the gray limestone aquifer is primarily intergrain and moldic (skeletal moldic), using the pore type terminology of Lucia (1995). Solution-enlarged pore spaces and minor intraparticle, root-mold, and boring porosity are distributed locally. Moldic porosity can be classified as "separate vug" or "touching vug" porosity and is related to grain packing. The rudstones of the gray limestone aquifer contain touching vug, separate vug, and intergrain porosity (fig. 7), whereas the floatstones are characterized by separate vug and intergrain porosity. In the rudstones with a matrix that contains intergrain porosity, moldic pore space is linked by both touching vugs and the intergrain pore space. In the floatstones with a matrix that contains an intergrain porosity, the moldic pore space is connected only by the intergrain pore space. Rocks containing pore spaces connected only by intergrain pores have relatively low values of hydraulic conductivity, whereas rocks containing touching vug pore space have relatively high values of hydraulic conductivity. Intergrain, moldic, and solution-enlarged pore spaces all contribute to the overall hydraulic conductivity of the rocks of the gray limestone aquifer.

Diffuse-carbonate and conduit flow are important ground-water flow mechanisms in the gray limestone aquifer. In diffuse-carbonate flow, the movement of water is partitioned within and flows through small-scale moldic and intergrain pore space contained in the rock. The pathways of ground-water movement in a conduit fluid-flow system are principally along bedding planes, fractures, joints, faults, and any other type of touching vugs expanded by chemical dissolution.

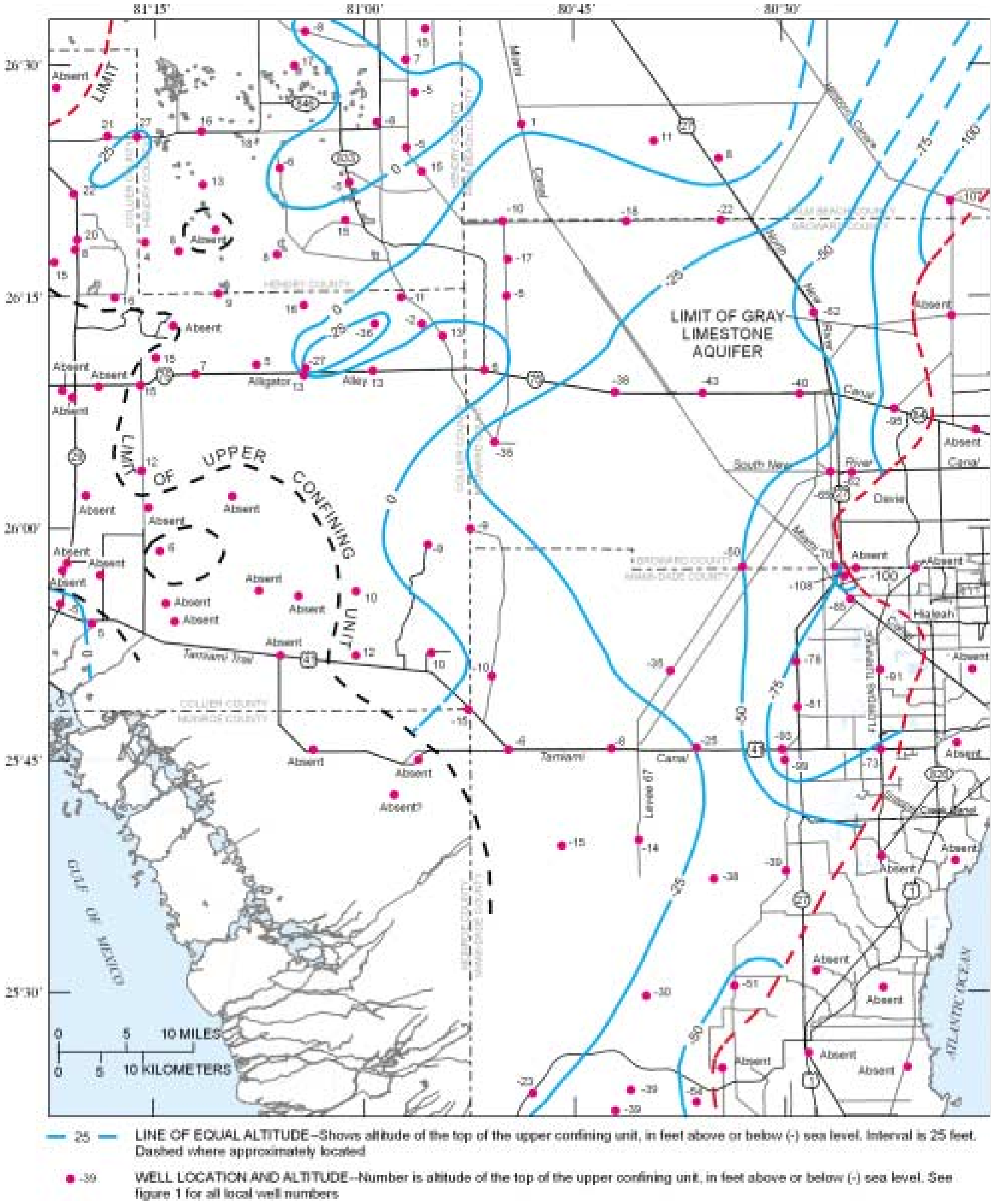


Figure 21. Altitude of the top of the upper confining unit of the gray limestone aquifer.

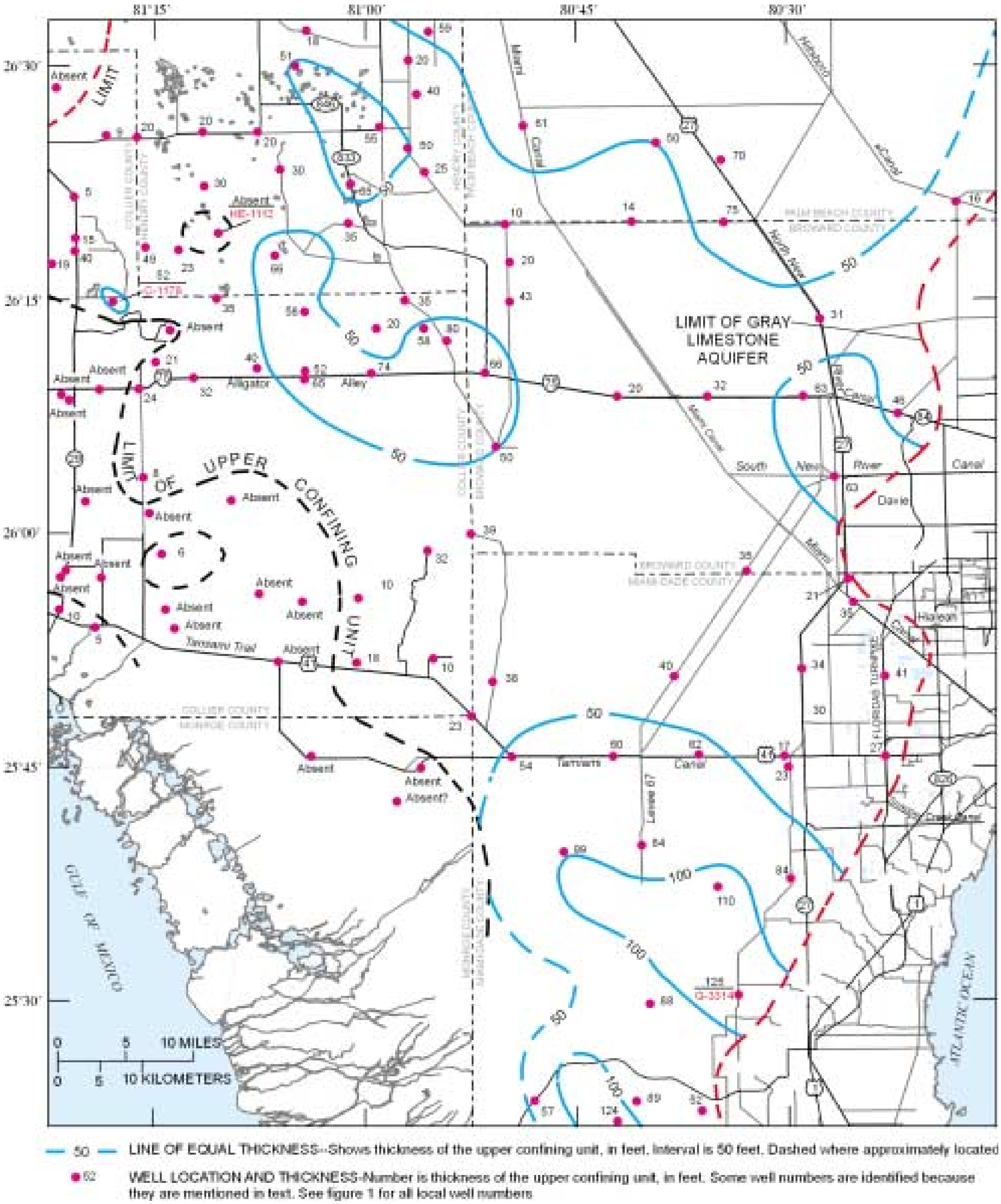


Figure 22. Thickness of the upper confining unit of the gray limestone aquifer.

Hydraulic Properties and Porosity Estimates

Estimates of the hydraulic properties of the gray limestone aquifer, including transmissivity, hydraulic conductivity, and the leakance were made by analysis of aquifer-test data. Additionally, qualitative estimates of porosity and hydraulic conductivity for the aquifer and bounding units were made visually by using a classification scheme developed by Fish (1988, table 8) during core sample description (appendix II). Quantitative estimates of these same parameters within the aquifer were made through laboratory analysis of core-plug samples. The “Core description and core sample analysis” section describes these methods in detail.

Historical Hydraulic Test Data

A total of 37 aquifer tests from published reports or made available from the files of private consultants were reviewed, including multiwell, single-well, specific-capacity, and step-drawdown tests (table 8). In three tests, the reported estimates were based on more than one of these methodologies. The least accurate of these methods used to determine transmissivity is the specific capacity test (Fish, 1988, p. 23); only five tests are based solely on this method. Two aquifer tests were performed within separate intervals of the gray limestone aquifer at the same site (table 8, map nos. 20 and 20A). Information in table 8 includes map number, site name, operator of the test, and source of information. The locations of all aquifer test sites are shown in figure 23.

On the basis of historical test data, the transmissivity of the gray limestone aquifer ranges from 5,800 to 160,000 ft^2/d, with storativity (storage coefficient) ranging from 1.0×10^{-5} to 6.0×10^{-4} (table 8). Where the aquifer is confined or semiconfined, reported values for leakance varied widely, ranging from about 8.6×10^{-7} to 2.3×10^{-2} 1/d. The test at sites with map numbers 33 to 36 (table 8) are interpreted to indicate unconfined conditions; these sites are located in western Collier County (fig. 23), and the aquifer in this area has been referred to as the water-table aquifer (Knapp and others, 1986). The average hydraulic conductivity of the gray limestone aquifer determined by aquifer test, as reported by others, ranged from 148 to 2,900 ft/d (table 8).

Aquifer Tests Conducted During this Study

Ten aquifer tests were conducted at six sites as part of this study (table 9). Four tests were multiwell tests and six were single-well tests. Five of the test sites are located in eastern Collier County and one is located in northern Monroe County. The multiwell tests were performed at the Bear Island Campground, Big Cypress Sanctuary, FAA Radar, and Trail Center sites (table 9, map nos. 38-40 and 42). The former two sites are located just to the north of Alligator Alley, and the latter two are located along Tamiami Trail (fig. 23). Single-well tests were performed at the Noble’s Farm, Bear Island Campground, Big Cypress Sanctuary, Alligator Alley East, and FAA Radar sites (table 9, map nos. 37, 38A, 39A, 40A, 40B, and 41).

All of the tests conducted in this study were of the gray limestone aquifer except two, which were single-well tests of sand aquifers within the Peace River Formation at the FAA Radar site. Hydraulic properties also were determined for the sand aquifer of the unnamed formation at the Bear Island Campground site using the multiwell test data collected during the test of the overlying gray limestone aquifer. This information was derived from numerical analysis of monitoring well drawdown data, which included data from well C-1141 completed in the sand aquifer (table 9, map no. 38B).

Analysis of aquifer test and heat-pulse flowmeter data and review of long-term water-level data suggest that the gray limestone aquifer is unconfined at the Bear Island Campground and FAA Radar sites, semiconfined at the Trail Center site, and confined at the Big Cypress Sanctuary site. Flow zones were determined at all four of these multiwell test sites using flowmeter data, and these zones together with other borehole geophysical logs and hydrogeologic units are shown in figure 24.

Analysis of the gray limestone aquifer test data at the FAA Radar site was made by using the Neuman (1972) unconfined solution (table 9). The site plan and time-drawdown plots for aquifer tests conducted at this site are shown in figure 25. The time-drawdown plots are from a monitoring well in the gray limestone aquifer (well C-1145) during the multiwell test and from the lower sand aquifer monitoring well (C-1143) during a single-well test (table 9). Data collected from single-well aquifer tests of the two sand aquifers of the intermediate aquifer system at this site (fig. 24) were evaluated using the Theis recovery solution (Theis, 1935). During the multiwell test of the gray limestone aquifer, no drawdown was observed in the monitoring wells completed in these well-confined sand aquifers, despite a 24-hour pumping period with an average pumping rate of 297 gal/min.

Table 8. Historical aquifer-test results for the gray limestone aquifer or equivalent aquifer

[Map numbers are shown in figure 23. Type of test: 1, multiwell test with solutions by Theis (1935), Cooper and Jacob (1946), Hantush and Jacob (1955) and other investigators; 2, single-well test with Theis (1935) recovery solution; 3, specific capacity test; and 4, step-drawdown test. Operator of test: SFWMD, South Florida Water Management District; USGS, U.S. Geological Survey; Missimer, Missimer and Associates; LB & G, Leggette, Brashears, and Graham. Units: ft, feet; ft^2/d, feet squared per day; ft/d, feet per day, 1/d, one over day. Other annotations: ?, top of depth interval open in production well is unknown; NR, not reported; and NA, not applicable given aquifer behavior or type of test; *, USGS local number]

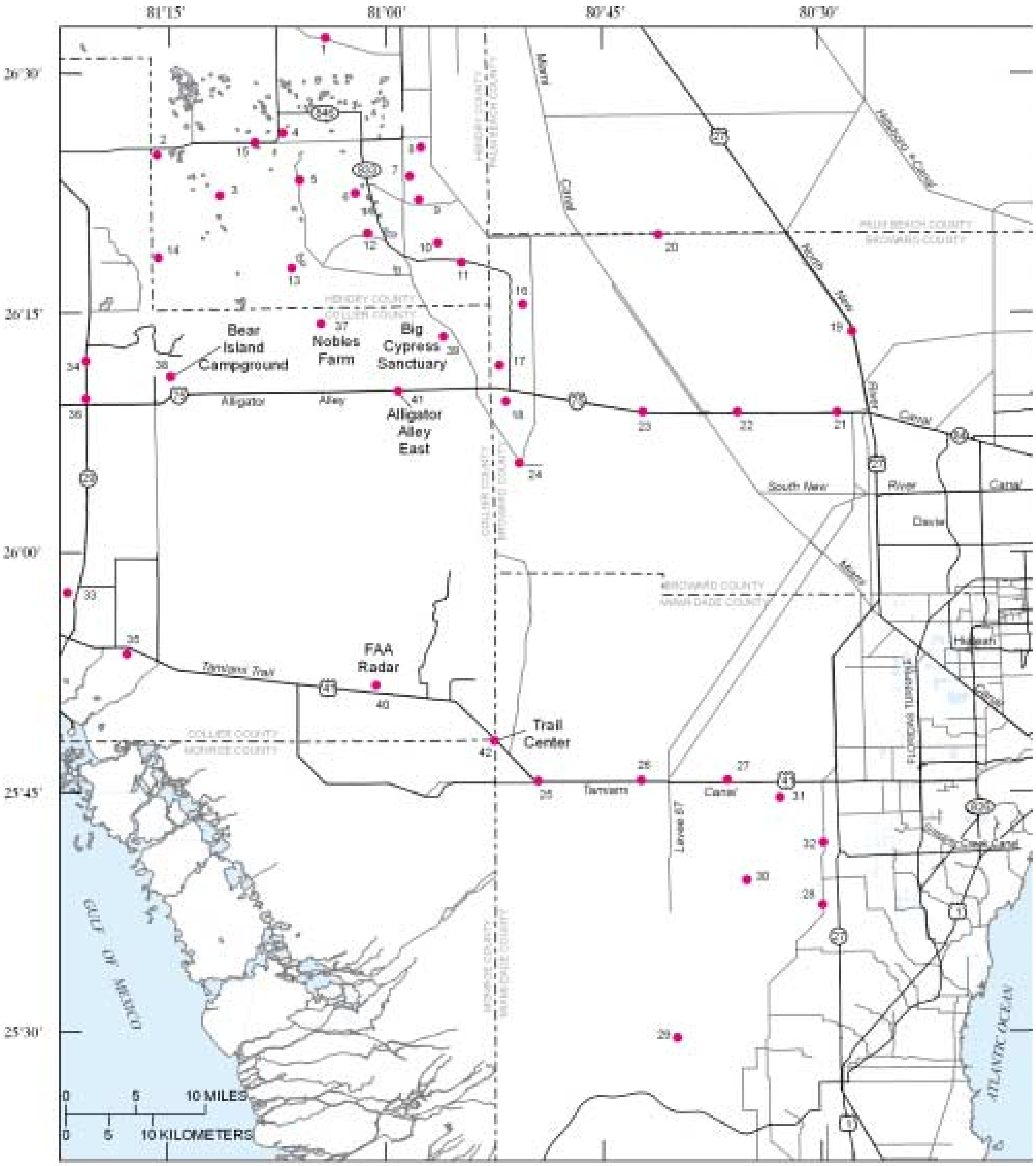
Map No.	Site name or land owner	Operator of test	Production well: Well number	Production well: Depth interval open (ft)	Type of test	Transmissivity (ft^2/d)	Storativity[1]	Leakance (1/d)	Average hydraulic conductivity (ft/d)	Source of information
1	Alico (site C)	SFWMD	HE-1035*	70 - 120	1	33,000	1.9×10^{-5}	8.6×10^{-7}	730	Smith and Adams (1988)
2	Collier Corporation	USGS	HE-286*	? - 40	1	125,000	4.2×10^{-4}	[2]2.5×10^{-3}	NR	Klein and others (1964)
3	Barron Collier	SFWMD	HE-1041*	40 - 80	1	61,000	1.2×10^{-4}	1.4×10^{-3}	1,700	Smith and Adams (1988)
4	U.S. Sugar Corporation, Rogers Ranch	Missimer	H-M-310	65 - 105	1	78,000	1.5×10^{-4}	5.5×10^{-3}	NR	Smith and Adams (1988)
5	Carl Gallagher	SFWMD	HE-1054*	70 - 100	1	88,000	2.1×10^{-4}	1.4×10^{-2}	2,900	Smith and Adams (1988)
6	Robert McDaniels	Hydro Designs	PW	60 - 118	1	62,000	2.1×10^{-4}	2.3×10^{-3}	NR	Smith and Adams (1988)
7	S & M Farms	USGS	HE-303*	? - 120	1	31,000	6.0×10^{-4}	[2]2.3×10^{-3}	NR	Klein and others (1964)
8	U.S. Sugar Corporation, South Division Ranch	Missimer	H-M-235	65 - 125	1	14,000	5.0×10^{-4}	1.5×10^{-4}	NR	Smith and Adams (1988)
9	U.S. Sugar Corporation, South Division Ranch	Missimer	H-M-301	76 - 124	1	44,000	2.6×10^{-4}	1.3×10^{-5}	NR	Smith and Adams (1988)
10	U.S. Sugar Corporation, South Division Ranch	Missimer	H-M-328	75 - 133	1	66,000	2.6×10^{-4}	3.3×10^{-4}	NR	Smith and Adams (1988)
11	Seminole Tribe	Murray-Milleson	PW	63 - 120	1	72,000	4.2×10^{-4}	2.5×10^{-4}	NR	Smith and Adams (1988)
12	Seminole Tribe (site 2)	SFWMD	HE-1021*	50 - 135	1	56,000	2.2 x 10-4	2.4×10^{-3}	560	Smith and Adams (1988)
13	Seminole Tribe (site 1)	SFWMD	HE-1061*	78 - 123	1	50,000	1.3×10^{-4}	1.3×10^{-4}	1,100	Smith and Adams (1988)
14	Hendry County Correctional Institute	LB & G	12	97 - 125	1	24,000	5.6×10^{-5}	NR	600	Smith and Adams (1988)
15	Collier Enterprises	Murray-Milleson	TPW	65 - 105	1	100,000	1.2×10^{-4}	3.5×10^{-3}	NR	Smith and Adams (1988)
16	Miccosukee Tribe (north site)	Murray-Milleson	TPW	55 - 135	1	44,000	3.0×10^{-4}	1.0×10^{-4}	NR	Murray-Milleson (1989)
17	Miccosukee Tribe (NW site)	Murray-Milleson	TPW	90 - 165	1	64,000	4.0×10^{-5}	4.0×10^{-5}	NR	Murray-Milleson (1989)
18	Miccosukee Tribe (south site)	Murray-Milleson	TPW	85 - 160	1	78,000	4.0×10^{-5}	3.0×10^{-5}	NR	Murray-Milleson (1989)
19	Twenty-Six Mile Bend	USGS	G-2312J*	110 - 140	1,3	22,000	6.0×10^{-5}	NR	650	Fish (1988)
20	North Everglades Central	USGS	G-2313B*	46 - 81	3	9,000	NA	NA	280	Fish (1988)

Table 8. Historical aquifer-test results for the gray limestone aquifer or equivalent aquifer (Continued)

[Map numbers are shown in figure 23. Type of test: 1, multiwell test with solutions by Theis (1935), Cooper and Jacob (1946), Hantush and Jacob (1955) and other investigators; 2, single-well test with Theis (1935) recovery solution; 3, specific capacity test; and 4, step-drawdown test. Operator of test: SFWMD, South Florida Water Management District; USGS, U.S. Geological Survey; Missimer, Missimer and Associates; LB & G, Leggette, Brashears, and Graham. Units: ft, feet; ft^2/d, feet squared per day; ft/d, feet per day, 1/d, one over day. Other annotations: ?, top of depth interval open in production well is unknown; NR, not reported; and NA, not applicable given aquifer behavior or type of test; *, USGS local number]

Map No.	Site name or land owner	Operator of test	Production well		Type of test	Trans-missivity (ft^2/d)	Storativity[1]	Leakance (1/d)	Average hydraulic conduc-tivity (ft/d)	Source of information
			Well number	Depth interval open (ft)						
20A	North Everglades Central	USGS	G-2313C*	106 - 146	4	26,000	NA	Very leaky	650	Fish (1988)
21	Alligator Alley East	USGS	G-2319X*	118 - 140	2	22,000	NA	NA	590	Fish (1988)
22	Alligator Alley Central	USGS	G-2320J*	93 - 167	4	67,000	NA	NA	910	Fish (1988)
23	Alligator Alley West	USGS	G-2330Z*	81 - 167	1,2,4	88,000	7.0×10^{-5}	NR	930	Fish (1988)
24	Southwest Everglades	USGS	G-2338C*	102.5 - 156	1	50,000	1.0×10^{-5}	Confined	890	Fish (1988)
25	Forty-Mile Bend	USGS	G-3301E*	101 - 149	1	39,000	NR	NR	780	Fish and Stewart (1991)
26	Tamiami West	USGS	G-3302E*	81 - 138	1	25,000	NR	NR	420	Fish and Stewart (1991)
27	Tamiami Central	USGS	G-3303E*	121 - 150	1	13,000	NR	NR	430	Fish and Stewart (1991)
28	Levee 31N	USGS	G-3311H*	145 - 173	3	5,800	NA	NA	210	Fish and Stewart (1991)
29	Context Road West	USGS	G-3394B*	110 - 145	1,3	14,000	NR	NR	400	Fish and Stewart (1991)
30	WWF-3	USGS	WWF-3	160 - 198	1	16,000	2.8×10^{-5}	Confined	424	Labowski and others (1988)
31	WWF-6	USGS	WWF-6	140 - 170	1	15,000	6.9×10^{-5}	Confined	523	Labowski and others (1988)
32	WWF-9	USGS	WWF-9	85 - 150	1	9,600	6.0×10^{-4}	2.3×10^{-2}	148	Labowski and others (1988)
33	Copeland	Missimer	CO-304	15 - 25	1	160,000	1.2×10^{-1} (specific yield)	NA	NR	Missimer and Associates (1981)
34	Site C-28	SFWMD	Unknown	10 - 39	3	120,000	NA	NA	NR	Knapp and others (1986)
35	Site C-30	SFWMD	Unknown	12 - 40	3	96,000	NA	NA	NR	Knapp and others (1986)
36	Site C-34	SFWMD	Unknown	0 - 53	3	130,000	NA	NA	NR	Knapp and others (1986)

[1]Aquifer at site nos. 33 to 36 is interpreted to be unconfined; aquifer at remaining sites interpreted to be confined or semiconfined.
[2]Value for leakance was determined from reanalysis of drawdown data (reported value found to be in error).



42 MAP NUMBER--Map number of aquifer test site. See tables 8 and 9 for map number, site name, and additional information. Site names are shown for sites where aquifer tests were conducted in this study

Figure 23. Location of aquifer test sites.

Table 9. Aquifer-test results from tests conducted during the course of the study

[Map numbers are shown in figure 23. Type of test: 1, multiwell test with solutions by Theis (1935), Cooper and Jacob (1946), or Hantush and Jacob (1955); 2, multiwell test with solution by Neuman (1972); 3, single well test with Theis (1935) recovery solution; and 4, multiwell test with numerical analysis using drawdown data in gray limestone and sand aquifers during same test. Units: ft, feet; ft^2/d, feet squared per day; ft/d, feet per day; 1/d, one over day. NA, not applicable given aquifer behavior or type of test]

Map No.	Site name	Production well		Type of test	Transmissivity (ft^2/d)	Storativity[1]	Leakance (1/d)	Estimated hydraulic conductivity (ft/d)[2]
		USGS local well number	Depth interval open (ft)					
Gray Limestone Aquifer								
37	Nobles Farm	C-1142	60 - 100	3	80,000	S/S′ = 0.44	NA	2,000
38	Bear Island Campground	C-1167	22 - 57	4	[3]200,000	2.0×10^{-4}	NA	4,000
38A	Bear Island Campground	C-1166	23 - 43	3	200,000	S/S′ = 0.19	NA	4,000
39	Big Cypress Sanctuary	C-1171	75 - 135	1	70,000	6.0×10^{-4}	NA[4]	1,100
39A	Big Cypress Sanctuary	C-1170	80 - 120	3	70,000	S/S′ = 1.5	NA	1,100
40	FAA Radar	C-1172	9 - 49	2	300,000	4.0×10^{-3}	[5]0.2	12,000
41	Alligator Alley East	C-1182	75 - 125	3	100,000	S/S′ = 1.1	NA	2,000
42	Trail Center	MO-188	89 - 114	1	90,000	4.0×10^{-4}	7.0×10^{-3}	1,200
Sand Aquifer								
38B	Bear Island Campground	C-1141[6]	88 - 108	4	840	8.0×10^{-5}	NA	20
40A	FAA Radar	C-1143	180 - 200	3	1,500	S/S′ = 1.0	NA	75
40B	FAA Radar	C-1144	120 - 130	3	180	S/S′ = 1.1	NA	14

[1]Gray limestone aquifer at site nos. 38 and 40 interpreted to be unconfined; gray limestone aquifer at remaining sites and all sand aquifers tested interpreted to be confined or semiconfined. S/S′ is ratio of storativity during drawdown to that of recovery.

[2]Estimated using full thickness of aquifer (see table 7 and Appendix II).

[3]Best fit to data was obtained assuming the aquifer is semiconfined, but long-term water-level data indicate aquifer is unconfined. A similar value for transmissivity was obtained by the Cooper-Jacob analysis of early time data.

[4]Test not run long enough to determine leakance.

[5]Specific yield.

[6]Used as monitoring well during test of gray limestone aquifer (map no. 38 above).

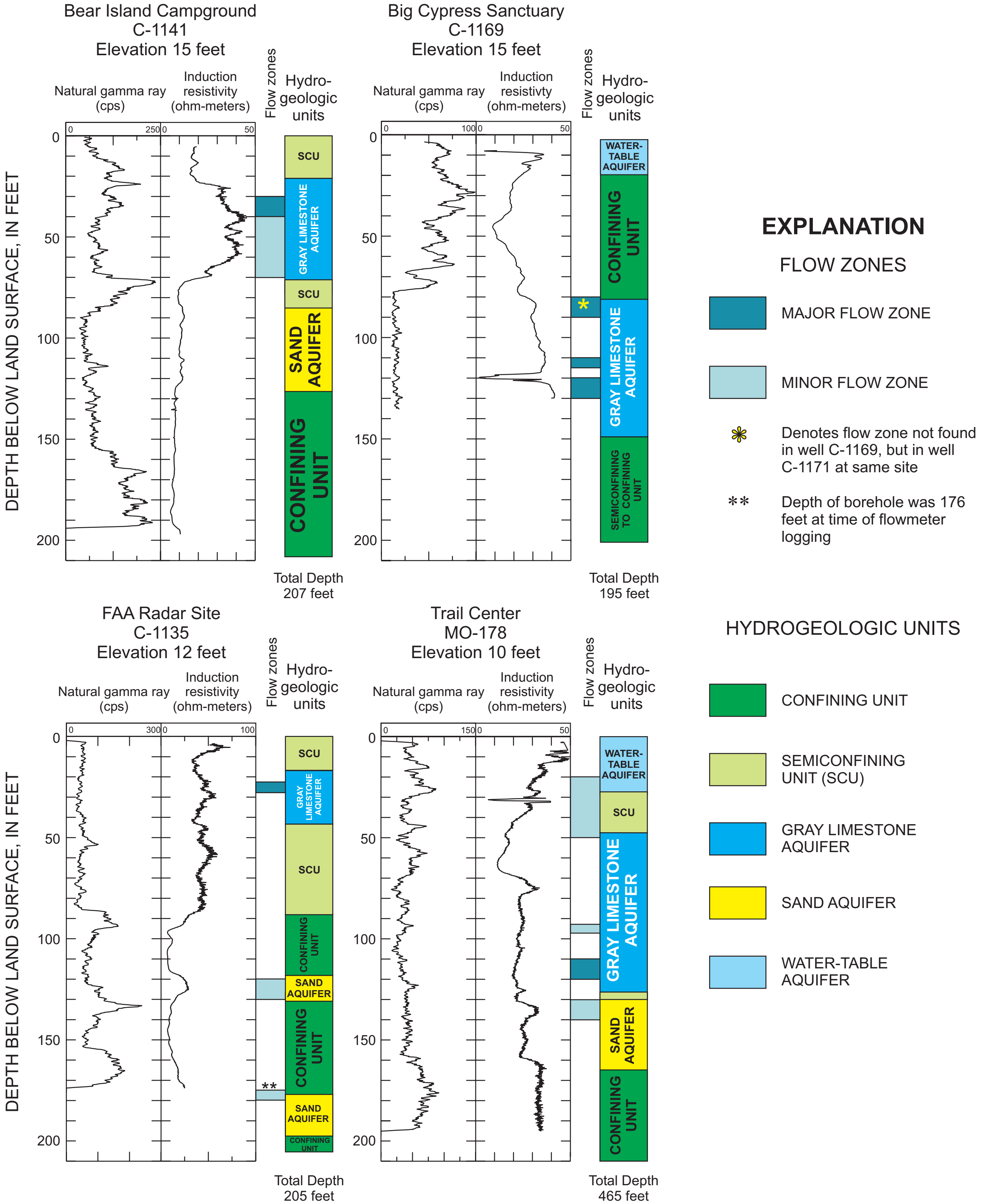
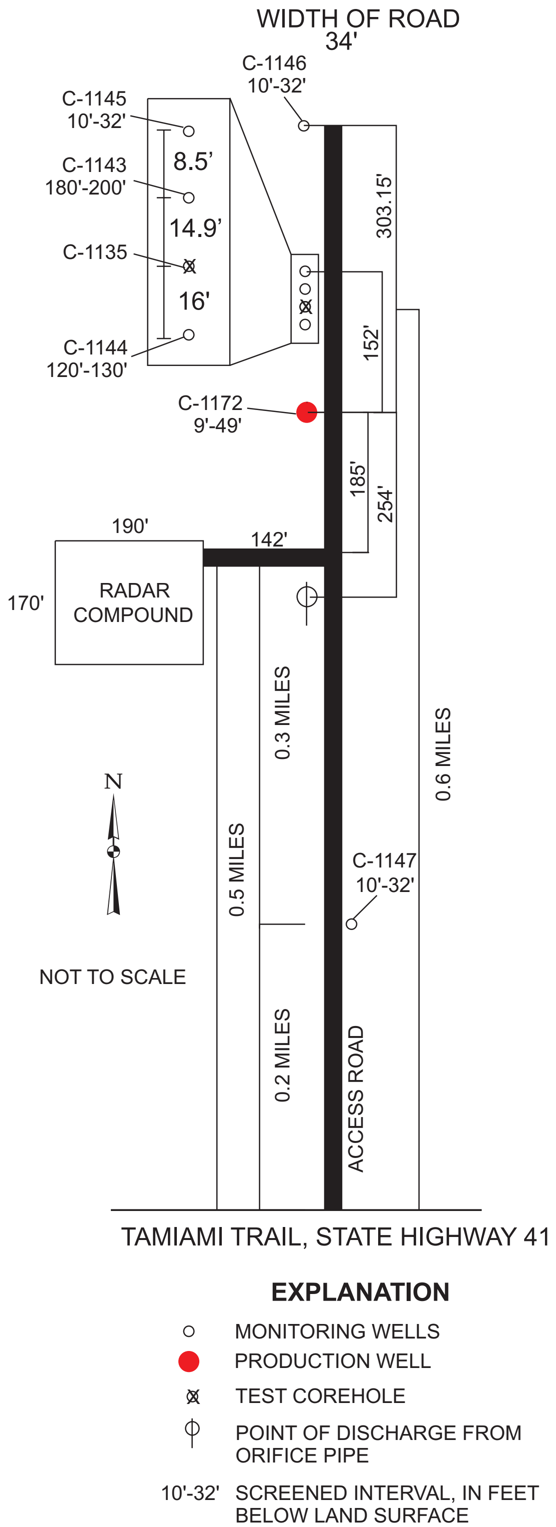
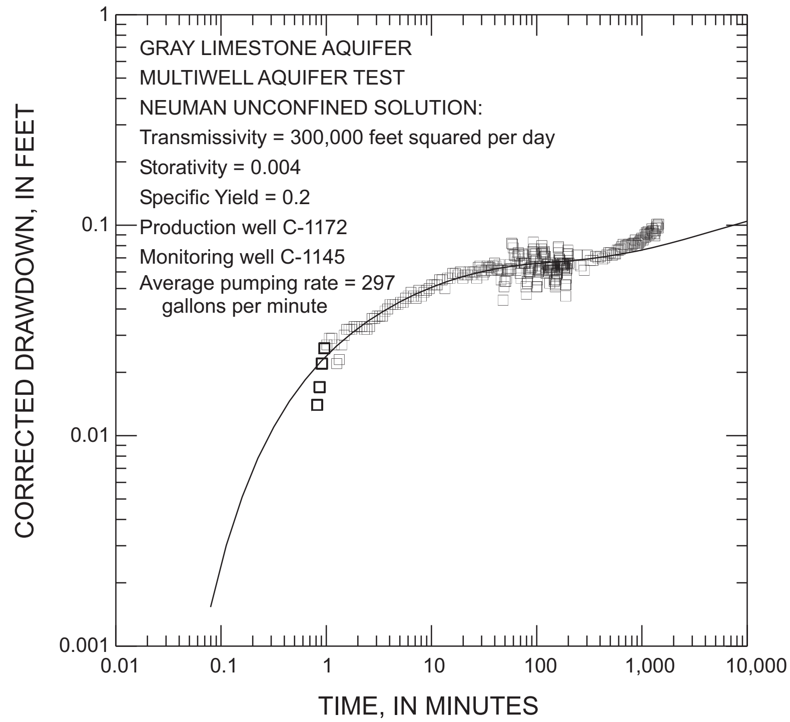


Figure 24. Borehole geophysical logs, flow zones, and principal hydrogeologic units for test wells at four sites where multiwell aquifer tests were conducted. The cps unit represents counts per second.





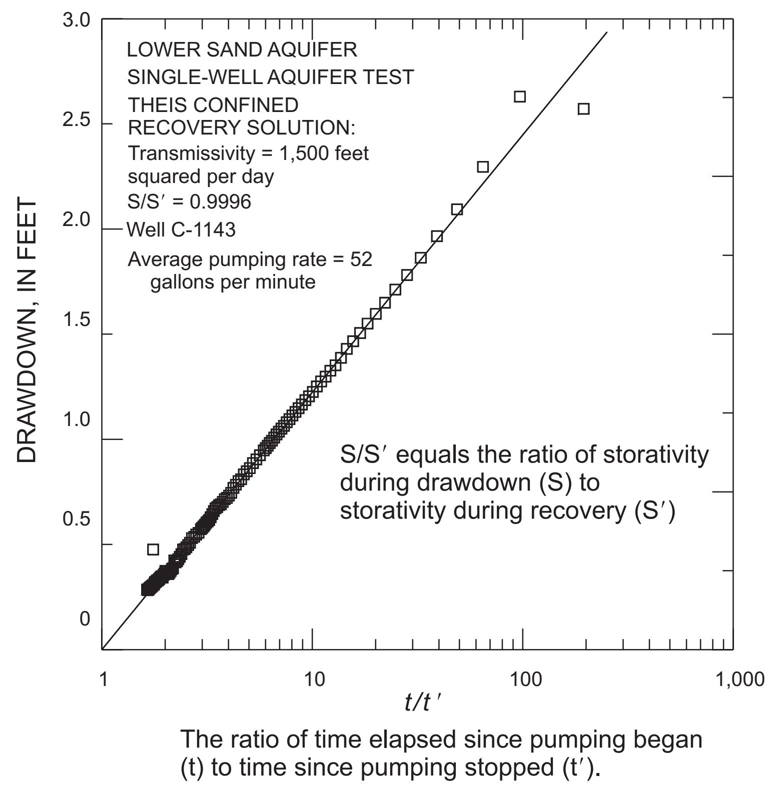


Figure 25. Site plan and time-drawdown plots for two aquifer tests conducted at the FAA Radar site. All wells are completed in the gray limestone aquifer, except for wells C-1143 and C-1144 which are completed in sand aquifers.

The average transmissivity value reported for the multiwell test of the gray limestone aquifer at the Trail Center site was 90,000 ft^2/d based on a composite analysis of monitoring wells MO-180, MO-182, and MO-185, all of which were screened in the lower part of the aquifer at about the same depths as the production well (fig. 26 and table 9). The production well (MO-178) was screened from 89 to 114 ft below land surface. Poorly permeable limestone containing a carbonate mud-rich matrix occurs at depths between 80 and 96 ft below land surface and separates the aquifer into upper and lower parts; and this unit provides some confinement within the aquifer based on water-quality data. Nevertheless, drawdown data from MO-187, screened from 70 to 80 ft below land surface in the upper part of the aquifer, gave a transmissivity of approximately 80,000 ft^2/d, which is similar to the value obtained from the wells in the lower part of the aquifer.

Core Analysis Data

A total of 32 limestone and sandstone core-plugs were horizontally cut from core samples: 30 of the samples were from the gray limestone aquifer, and 2 were from just below the base of the aquifer. Porosity measured from these plugs ranged from 9.5 to 45.1 percent, and horizontal permeability to air ranged from 189 to greater than 20,000 mD (millidarcies) (table 10). Equivalent hydraulic conductivity was calculated from the permeability values and ranged from 0.5 to greater than 55 ft/d (table 10). Permeability could not be determined for five (16 percent) core plugs because permeability exceeded the upper limit of the laboratory instrumentation (20,000 mD) or because of a poor seat with the portion of the instrument holding the plug. Plots of porosity as a function of the logarithm of permeability and as a function of hydraulic conductivity (fig. 27) suggest no linear relationships.

Core-plug derived measurements of hydraulic conductivity are one to two orders of magnitude less than aquifer-test-derived hydraulic conductivity estimates. For example, at the Trail Center site, the hydraulic conductivity determined for the gray limestone aquifer by aquifer testing was 1,200 ft/d (table 9, map no. 42). However, horizontal hydraulic conductivity determined from analysis of three core plugs taken from the aquifer at the site averaged only 23 ft/d (table 10, wells MO-185 and MO-187). This discrepancy is due to a large scale difference in the volume of the aquifer measured. However, the core measurements can be considered to indicate a range for the minimum hydraulic conductivity within the gray limestone aquifer because core plugs do not include large-scale pore spaces.

Distribution of Transmissivity, Hydraulic Conductivity, and Degree of Confinement

Flow-zone thicknesses determined by using flowmeter logs in combination with analysis of aquifer test data indicate that flow is concentrated through thin, high hydraulic conductivity zones within the gray limestone aquifer, forming a flow system that is partially conduit in nature (fig. 24). Flow zones are usually only 5 to 10 ft thick and are separated by intervals of low to moderate hydraulic conductivity that can function as semiconfining units within the aquifer. Only one flow zone in the gray limestone aquifer was found at the FAA Radar site, and its depth is from 23 to 28 ft below land surface. A hydraulic conductivity value for the aquifer at this site of 12,000 ft/d was calculated based on the thickness (25 ft) of the aquifer and the estimated transmissivity (table 7, well C-1135 and table 9, map no. 40). If the thickness of only the flow zone is used, the hydraulic conductivity would be much larger. At the FAA Radar site, some vuggy porosity was observed in core samples collected from this flow zone. Additionally, core recovery in well C-1135 (at the FAA Radar site) for the interval 20 to 30 ft below land surface was only 7 percent, compared to an average of 66 percent for the Ochopee Limestone intervals in all of the continuous cores for which descriptions are given in appendix II. The poor recovery in this 10-ft interval in well C-1135 could have resulted from large solution openings in the rock affecting its structural integrity during coring. The high hydraulic conductivity of the thin flow zone at the FAA Radar site is attributed to solution openings, rather than the moldic and intergranular porosity common in the aquifer.

Flow zones tend to be developed in the lower part of the gray limestone aquifer where the aquifer is confined or semiconfined; for example, at the Big Cypress Sanctuary and Trail Center sites (fig. 24) and at the Noble's Road site (fig. 1 and table 1, well C-1139). The upper part of the aquifer in these areas is commonly poorly consolidated possibly due to poor cementation.

Aquifer tests conducted during this study suggest a much higher upper limit for transmissivity than previously reported for the gray limestone aquifer;

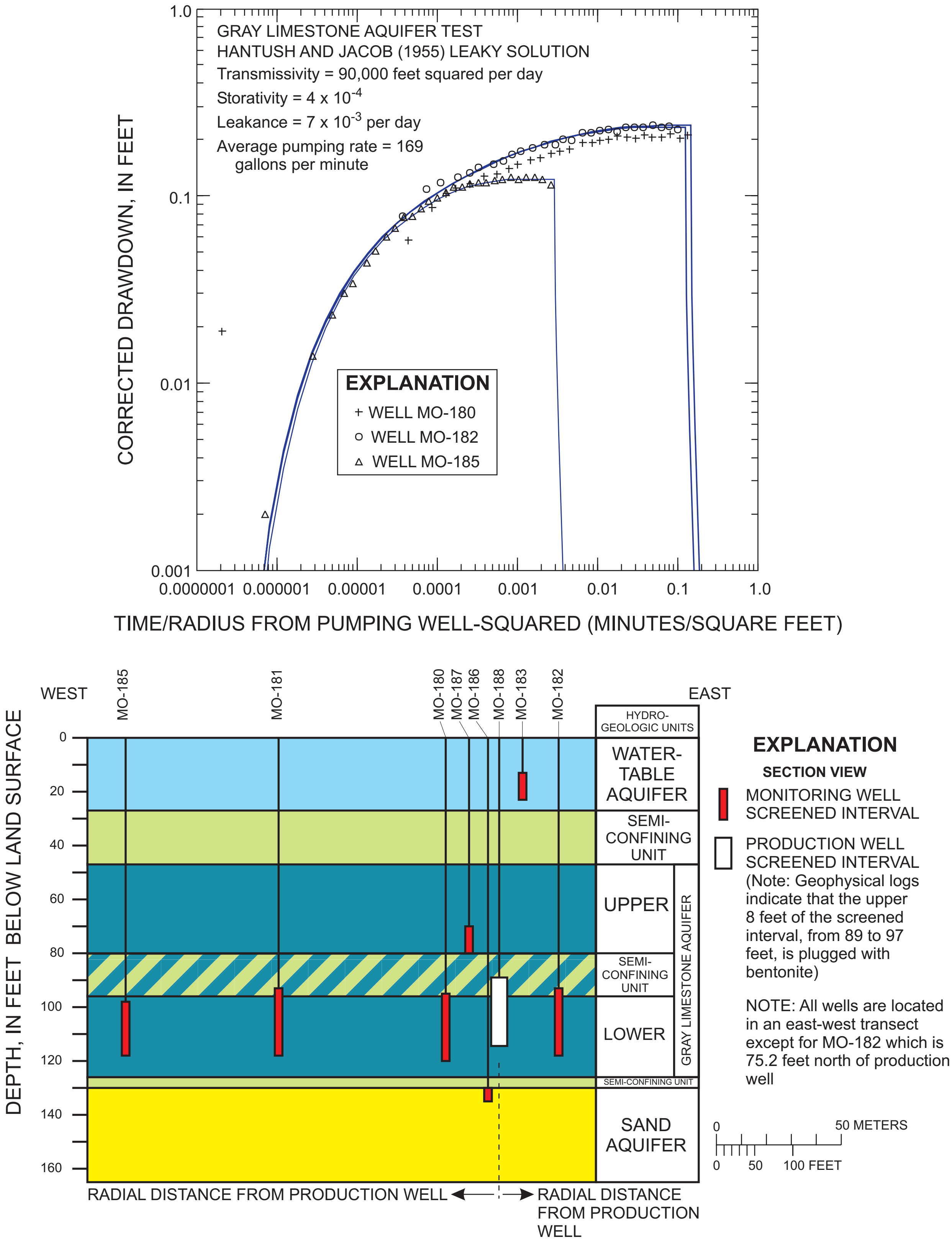


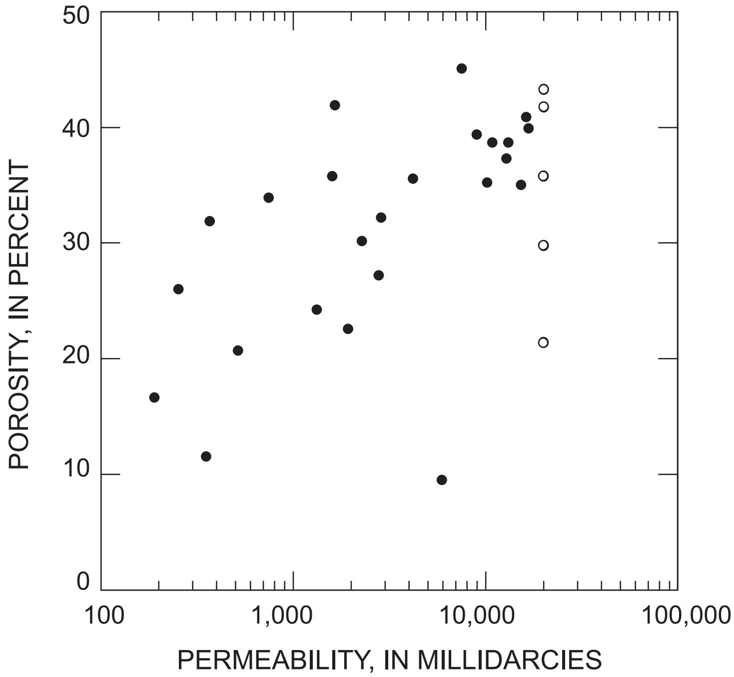
Figure 26. Time (over radius squared) drawdown plot and section showing screened intervals in wells for aquifer test of gray limestone aquifer at the Trail Center site.

Table 10. Core analysis data for limestone and quartz sandstone from the gray limestone aquifer

[Each analysis is of a 1- to 1.5-inch diameter plug taken from the depth or depth interval given, and the direction of permeability measurement was horizontal. The upper limit of instrument for measaurement of permeability(greater than 20,000 millidarcies or 55 feet per day where noted) was exceeded because of very high permeability or poor seat of sample with instrument. Annotations: ft, feet; mD, millidarcies; ft/d, feet per day; g/cm^3, grams per cubic centimeter; >, greater than the value]

USGS local well number	Site name or other well identifier	Depth (ft)	Porosity (percent)	Permeability to air[1] (mD)	Hydraulic conductivity[2] (ft/d)	Grain density (g/cm^3)
C-1141	Bear Island-D	67.5	39.4	8,985	25	2.64
C-1143	RD (FAA Radar)	20 - 25	11.5	350	1.0	2.69
		25 - 30	21.4	>20,000	>55	2.70
		30 - 35	9.5	5,888	16	2.70
		50 - 58[3]	27.2	2,767	7.6	2.64
C-1166	Bear Island-2	28 - 43	37.3	12,277	35	2.70
C-1169	BSC-1	109.6	43.3	>20,000	>55	2.69
		130	35.8	1,593	4.4	2.72
		138.2	26.0	253	.7	2.73
C-1183	Baker's Grade	44	41.7	>20,000	>55	2.75
		51	32.2	2,873	7.9	2.76
		56.3	31.9	366	1.0	2.72
		66	40.9	16,172	44	2.68
		76	35.2	10,203	28	2.67
G-3301	DAC-10C	104	38.7	10,802	30	2.70
		112	Unsuitable[4]	6,249	17	2.69
		118.5	Unsuitable[4]	10,211	28	2.68
G-3671	B-1, L-30	128.0	20.7	512	1.4	2.76
G-3673	B-2B, L-31	127.5	35.0	15,241	42	2.77
G-3674	B-3 Miami Canal	134.9	22.6	1,914	5.2	2.68
		140.2	24.2	1,316	3.6	2.68
HE-1110	L-3 Deep	55 - 60	29.8	>20,000	>55	2.68
		140 - 145	33.9	743	2.0	2.68
MO-184	Golightly	72 - 82	30.2	2,265	6.2	2.72
MO-185	TC-5	70 - 80	38.7	13,107	36	2.69
		80 - 90	45.1	7,520	21	2.69
MO-186	TC-6	130 - 135[3]	16.7	189	.5	2.69
MO-187	TC-7	58 - 73	35.6	4,192	12	2.75
		73 - 80	35.8	>20,000	>55	2.70
PB-1704	Sod Farm	84.9	24.8	Unsuitable[5]	Unsuitable[5]	2.75
		89.7	39.9	16,702	46	2.72
		171.3	41.9	1,648	4.5	2.66

[1]Not corrected for Klinkenberg effect.
[2]Calculated from measured air permeability value using factor of 1 mD equal to 0.00274 ft/d.
[3]Sample taken from just below the base of the gray limestone aquifer.
[4]Sample unsuitable for porosity measurement.
[5]Sample unsuitable for permeability measurement.



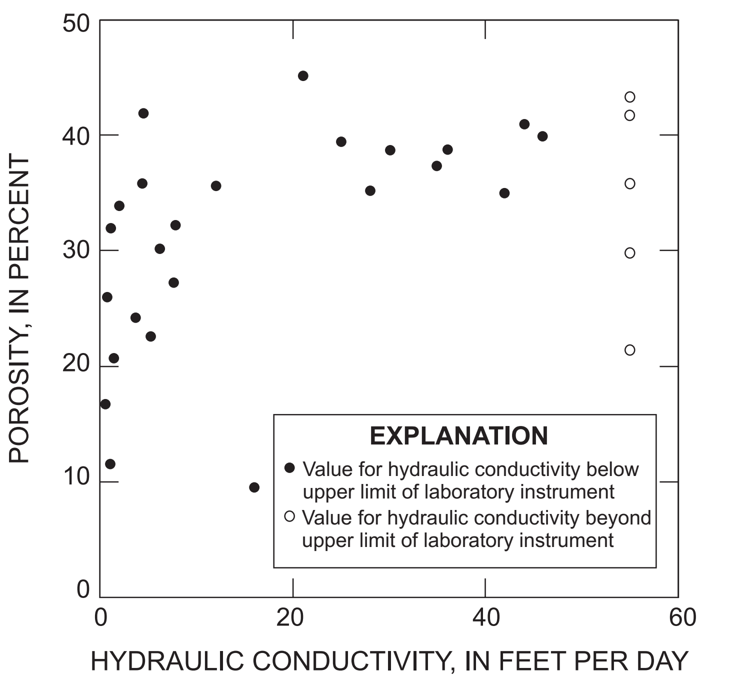


Figure 27. Relations between permeability and porosity and between hydraulic conductivity and porosity of limestone and sandstone from the gray limestone aquifer as determined by core analysis. Direction of permeability measurement is horizontal. Upper limit of the laboratory instrumentation is 20,000 millidarcies (55 feet per day). Data from table 10.

transmissivity is as high as 300,000 ft^2/d (table 9, map no. 40). A transmissivity distribution map of the gray limestone aquifer was constructed (fig. 28) by using transmissivity values determined from aquifer tests (tables 8 and 9) and transmissivity values estimated at test corehole sites where no aquifer tests were performed. These latter transmissivity estimates represent a “synthetic” value. They are based on aquifer thickness, written core descriptions, flowmeter log data, depth to the top of the aquifer, and the location of the site with respect to the regional depositional setting.

The transmissivity distribution map shows two large areas with transmissivity greater than 50,000 ft^2/d, both of which extend in a southeast direction (fig. 28). One area extends through southern Hendry County into west-central Broward County and has a transmissivity as high as 125,000 ft^2/d; the second area extends from west-central Collier through eastern Collier County to northern Monroe County with a transmissivity as high as 300,000 ft^2/d. The orientation of these areas of higher transmissivity could be related to a depositional trend for the Ochopee Limestone. Areas where transmissivity is less than 50,000 ft^2/d occur in southern Palm Beach County, northern and east-central Broward County, most of Miami-Dade County, and parts of Hendry County (fig. 28).

Alternatively, in the area of higher transmissivity extending through eastern Collier County, high values could be related to the structural position of the aquifer. In this area, the top of the aquifer is close to land surface and the upper confining unit is usually thin (less than 20 or 30 ft thick) or absent (fig. 22). At the Bear Island Campground and FAA Radar sites in this area, where the upper semiconfining unit is 21 ft thick or less, aquifer tests and long-term water-level data indicated the gray limestone aquifer is unconfined (fig. 28, map nos. 38 and 40). High hydraulic conductivity in the aquifer in this area could be, in part, related to greater rates of recharge of meteoric waters to the aquifer than in areas where the aquifer is buried more deeply and is better confined. Greater recharge rates could enhance carbonate dissolution in the aquifer.

A review of the hydraulic conductivity estimates (tables 8 and 9) and their location (fig. 23) indicate a general increase from east to west in hydraulic conductivity. A transect of aquifer tests along Alligator Alley illustrate this increase; hydraulic conductivity increases from 590 ft/d in central Broward County (fig. 23, map no. 21) to about 1,000 ft/d near the

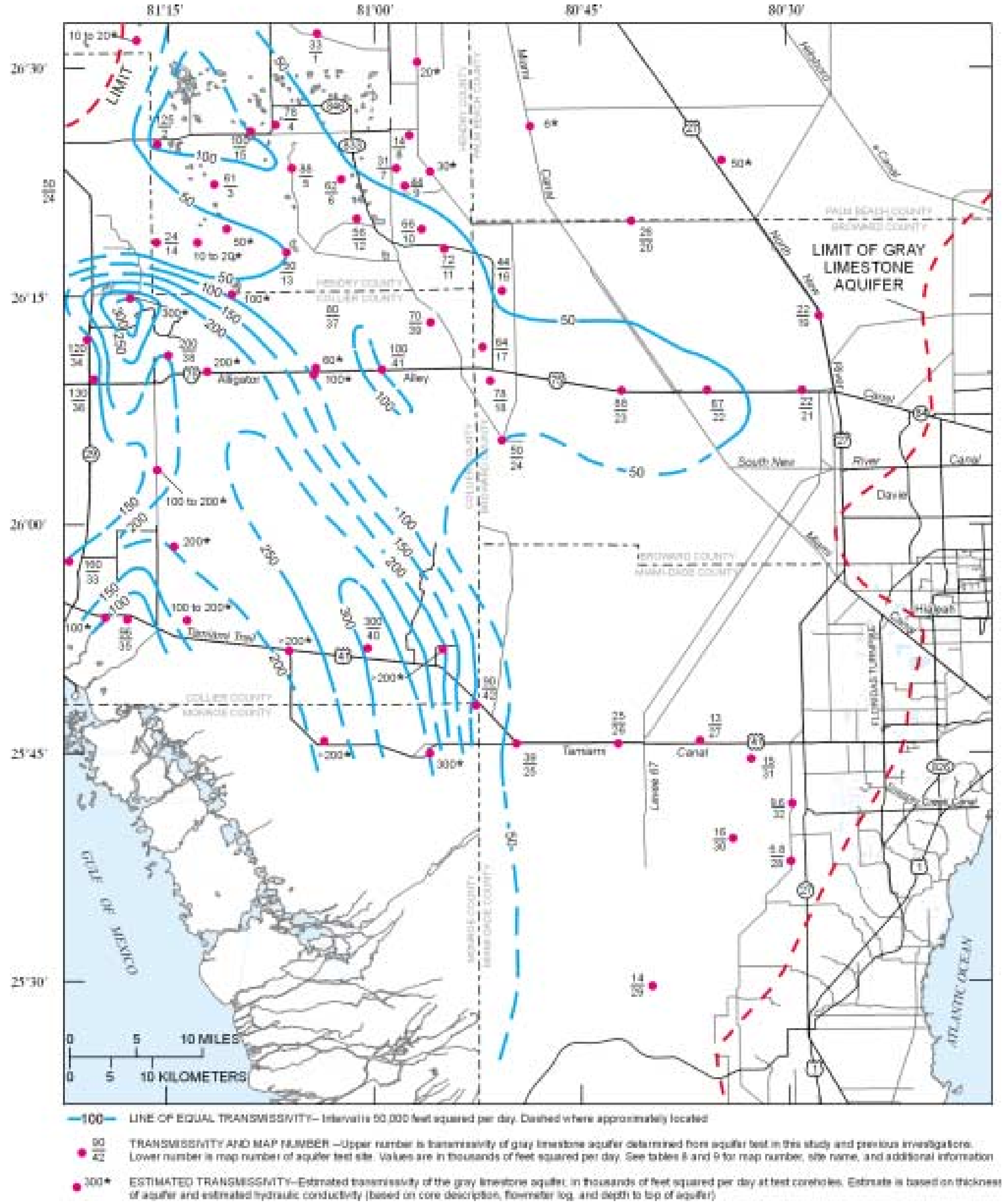


Figure 28. Distribution of transmissivity of the gray limestone aquifer in the study area.

Broward-Collier County line (map nos. 23, 24, and 39), to 2,000 ft/d at the Alligator Alley East site (map no. 41), and to 4,000 ft/d at the Bear Island Campground site in central Collier County (map no. 38). The lowest hydraulic conductivity estimates range from 148 to 523 ft/d, and these conductivities occur in Miami-Dade County near the eastern limit of the gray limestone aquifer (map nos. 28-32) and along the Broward-Palm Beach County line (map no. 20). An east-to-west shallowing of the depositional profile of the Ochopee Limestone carbonate ramp contributes to this spatial trend in hydraulic conductivity.

Leakance, which is the vertical hydraulic conductivity of the confining unit divided by its thickness, can be used to provide an indication of the degree of confinement of the aquifer. For purposes of this discussion, an aquifer is considered to be well confined, or have “good confinement,” if leakance was less than 1.0×10^{-3} 1/d. Sites where leakance was determined by aquifer testing to be less than 1.0×10^{-3} 1/d or the behavior of the aquifer was described as confined or well confined (tables 8 and 9) are shown in figure 29. These sites are located in southern Hendry County, western Broward County, and central Miami-Dade County and are in areas where the thickness of the confining unit approaches or is more than 50 ft. However, confining bed thickness did not necessarily prove to be a determinant of confinement. For example, the reported leakance at a site in central Hendry County (fig. 29 and table 8, map no. 1) was 8.6×10^{-7} 1/d, but the thickness of the upper confining unit is only 18 ft. Applying the 50-ft thickness criteria, areas where the aquifer should also be well confined include northeastern Collier County, south-central and southwestern Palm Beach County, and west-central and southern Miami-Dade County (fig. 29). A leakance value of 1.0×10^{-3} 1/d multiplied by a confining unit thickness of 50 ft gives an average vertical hydraulic conductivity of 0.05 ft/d. Review of leakance data and confining unit thickness (table 8 and fig. 29) indicates that the average vertical hydraulic conductivity is often less than this value in areas where the aquifer is well confined. A hydraulic conductivity of 0.05 ft/d is in the “very low” category as defined by Fish (1988), and lithologies in this category include clay, silt, and lime mud (Fish, 1988, table 8).

In some areas, the unnamed formation below the gray limestone aquifer contains a sand aquifer (figs. 12 and 13), and some degree of confinement separating the two aquifers exists. This is true in parts of Collier County, for example at the Bear Island Campground site (fig. 1, well C-1141), Trail Center site (fig. 1, well MO-178), and Doerr's Lake site (fig. 1, well C-1137). Some confinement between these aquifers is suggested on the basis of lithology, analysis of core samples, analysis of aquifer test and flowmeter data, and changes in water quality and hydraulic head.

At the Bear Island Campground site, the semiconfining unit between the gray limestone and the underlying sand aquifer is about 14 ft thick and consists of very fine sand (fig. 24). Disparate conditions exist between the two aquifers, as indicated by water-quality and water-level data collected on August 28, 1998. Chloride concentration was 61 mg/L (milligrams per liter), in water from the gray limestone aquifer and 840 mg/L in water from the sand aquifer. The water level in the gray limestone aquifer was about 0.6 ft below that in the sand aquifer. Numerical analysis of multiwell aquifer test data at this site (table 9) indicated that this semiconfining unit has a vertical hydraulic conductivity of 0.3 ft/d.

At some sites, the only confinement between the two aquifers could be a thin layer or layers of dense limestone or sandstone that are less than 1 ft thick. At the Trail Center site in northern Monroe County (fig. 1, well MO-178), the base of the gray limestone aquifer was penetrated at a depth of 126 ft below land surface. Core plug analysis of a sample of dense limestone recovered between the depths of 130 to 135 ft below land surface in well MO-186 (an offset monitoring well at the site) produced a horizontal hydraulic conductivity of about 0.5 ft/d; vertical hydraulic conductivity could be considerably less. Additional support for some confinement at the base of the aquifer at this site was provided by flowmeter log data collected in the test corehole; these data indicated there is a vertical barrier to flow between the depths of 110 to 130 ft below land surface.

Water Levels and Hydraulic Gradient

Continuous ground-water levels were measured in the gray limestone aquifer in September 1998 from five wells at five sites (fig. 30). Four of the wells were at the sites where multiwell aquifer tests were conducted (fig. 23, map nos. 38-40 and 42), and the other well was at the Noble’s Farm site (fig. 23, map no. 37). A tidal effect is apparent in wells at the Big Cypress Sanctuary (fig. 23, map no. 39) and Trail Center site (fig. 23, map no. 42) where the gray limestone aquifer is confined to semiconfined. The tidal signal is expressed by two small daily peaks. The pronounced drops (0.1 ft or more) often occurring each day during the afternoon at the Bear Island Campground site (fig. 23, map no. 38) could be caused by evapotranspiration.

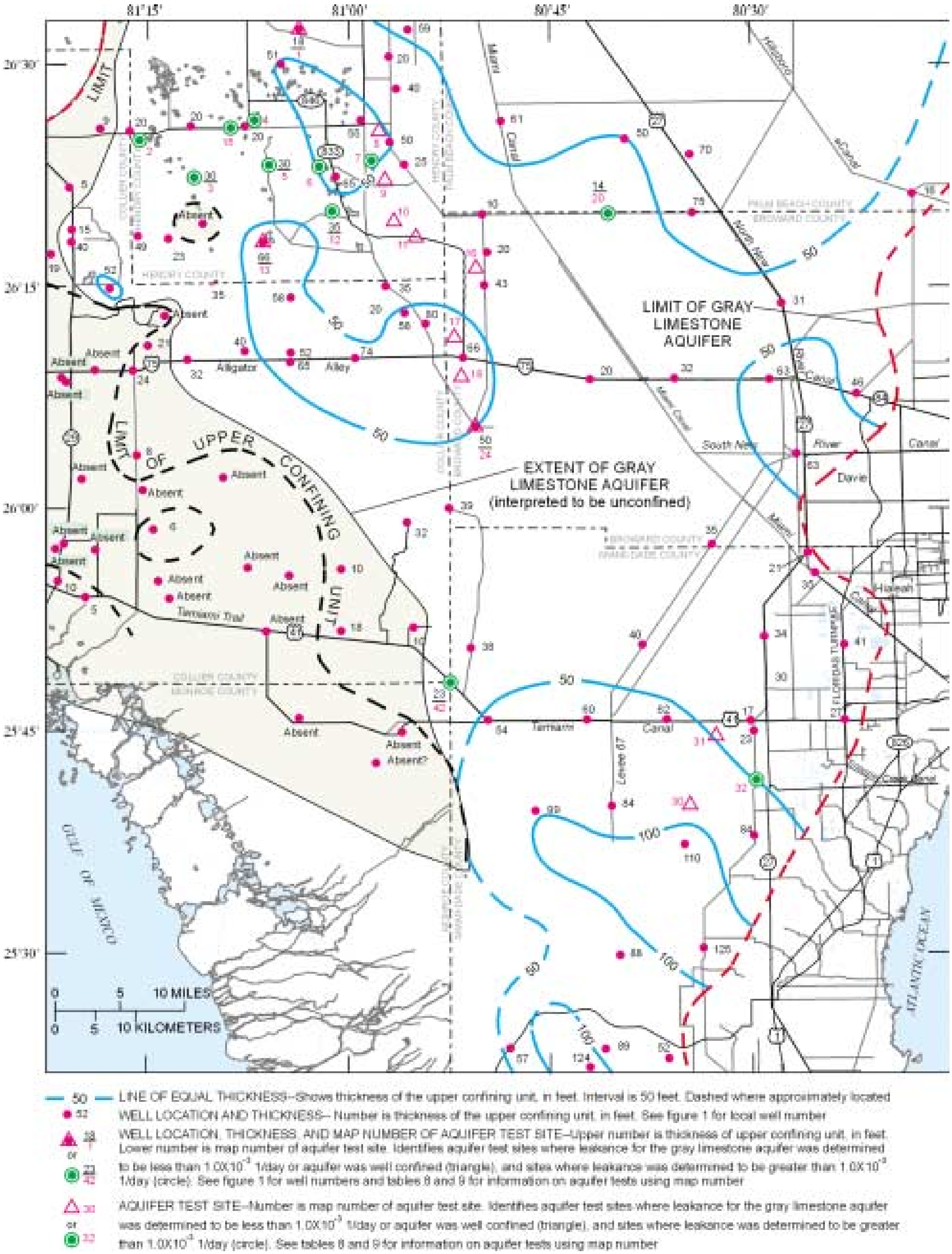


Figure 29. Thickness of upper confining unit and leakance of the gray limestone aquifer.

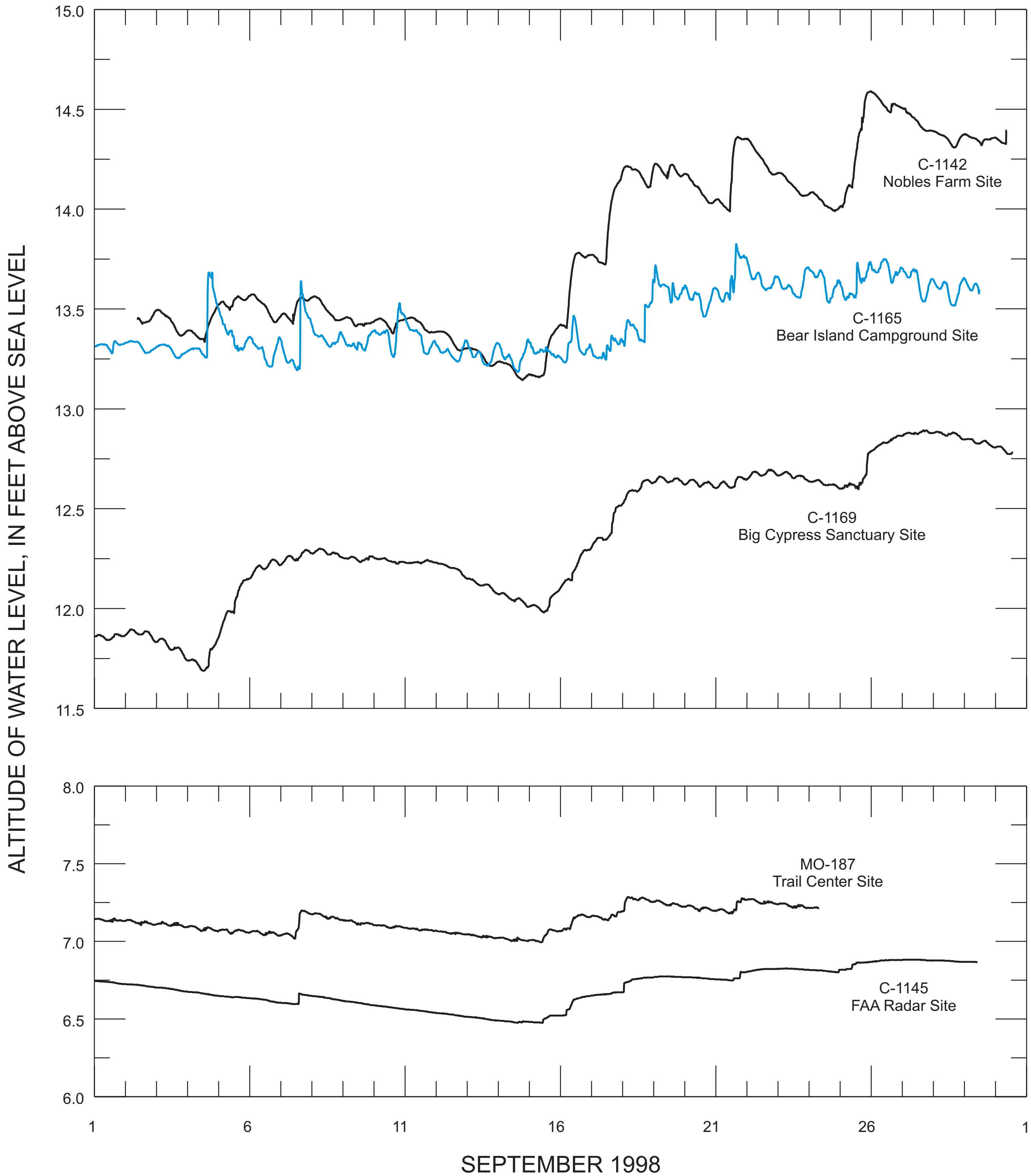


Figure 30. Hydrographs of five wells screened in the gray limestone aquifer in September 1998. Chart begins at 12:00 a.m., September 1. Well locations are shown in figure 1.

Water-level measurements of wells completed in the gray limestone aquifer were used to construct a synoptic potentiometric map showing hydrologic conditions for September 29, 1998 (fig. 31), which is close to the peak of the wet season (June through October). All but 4 of the 53 wells used to construct this map were measured on September 29, 1998. Two were measured on October 3, 1998, and two were estimated on the basis of the average late September 1986-95 levels. Discrete water-level data collected for the synoptic map are provided in table 11. For the purpose of comparison with the level in the gray limestone aquifer, water levels (at some sites) also were measured at the same time in the water-table aquifer and nearby surface-water stations on canals (table 11).

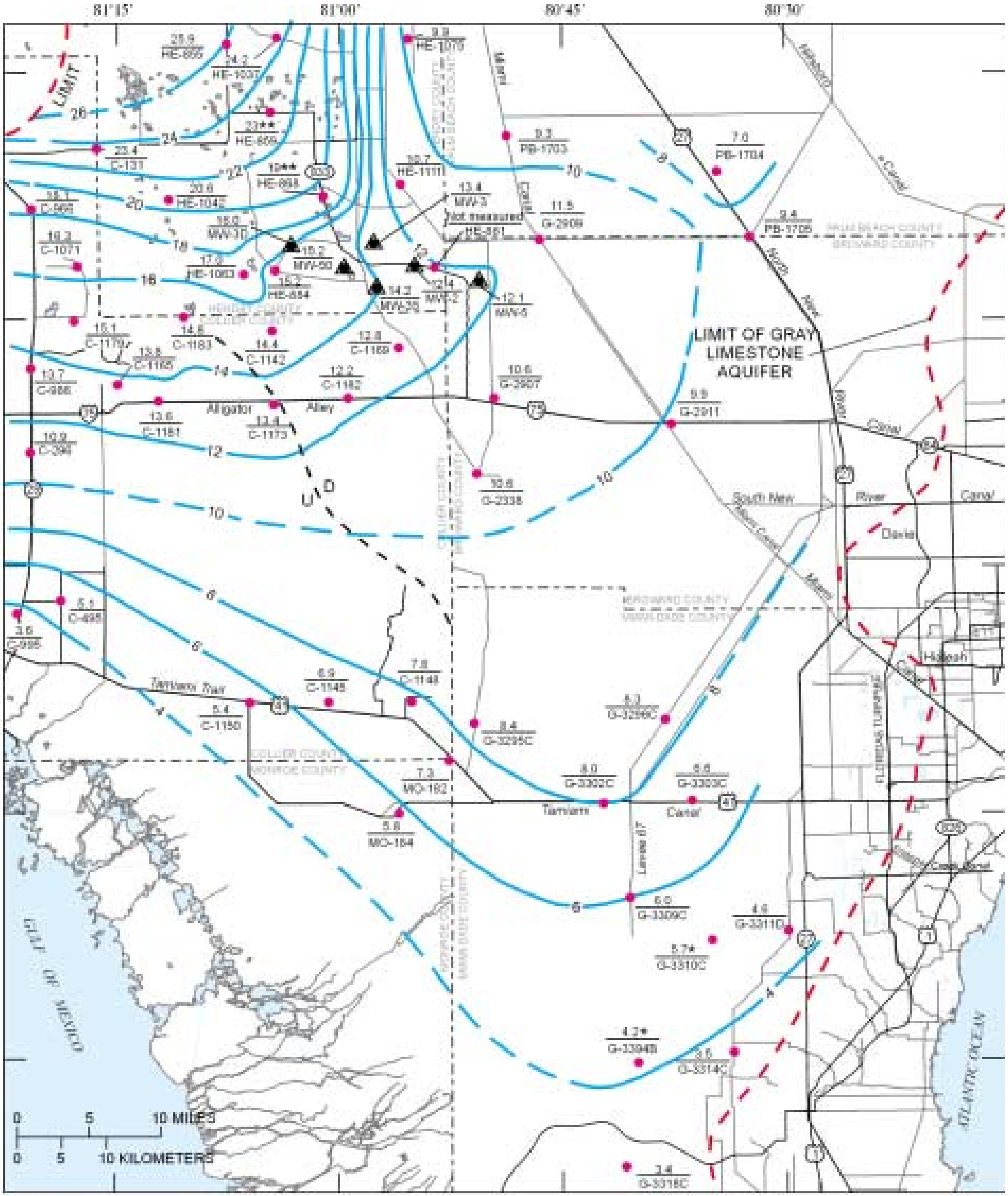
Water levels in the gray limestone aquifer ranged from as much as 26 ft above sea level in the far northwestern part of the study area in central Hendry County to less than 4 ft above sea level in coastal areas in Collier, Monroe, and Miami-Dade Counties (fig. 31). The direction of ground-water flow is to the south or southwest in part of southern Hendry County, most of Collier County, Monroe County, and western Miami-Dade County. Farther east in central Miami-Dade County, most of Broward County, and parts of eastern Collier and Hendry Counties, flow is to the east or southeast. Potentiometric surface contours form a large southeast plunging nose that extends from southern Hendry County to the east and southeast into Broward and Miami-Dade Counties and a small part of Palm Beach County.

The major recharge area for the aquifer is in central and southern Hendry County, some of which is north of the study area. In the major recharge area the potentiometric surface and land-surface elevation are high, and most recharge occurs where the upper confining unit is thin or absent (fig. 29). Comparison of water levels measured in the overlying water-table aquifer to the level measured in the gray limestone aquifer at the same site gives an indication whether there is potential for recharge (level in water-table aquifer is higher than level in the gray limestone aquifer) or discharge (level in water-table aquifer is lower than level in the gray limestone aquifer) to occur. In Hendry and northwestern Collier Counties, potential recharge was indicated at all five sites where both levels were measured on September 29, 1998. At these sites, the water level in the gray limestone aquifer ranged from 0.40 to 1.30 ft lower than the level in the water-table aquifer (table 11).

Areas of potential discharge were indicated to occur in eastern Collier, Broward, and Miami-Dade Counties on September 29, 1998. In this area, water levels in both the water table and gray limestone aquifers were measured at 12 sites, with discharge indicated at 9 of these sites. The water level at the nine sites in the gray limestone aquifer ranged from 0.09 to 2.15 ft higher than the water level in the water-table aquifer (table 11). Of the remaining three sites, two were located at the boundary of areas of impounded surface water where the level in the water table aquifer would be expected to be artificially elevated.

The area with the highest potentiometric gradient in the study area is in eastern Hendry County just to the west of the L-2 and L-3 Canals (figs. 3 and 31). The gradient here is as steep as 3 ft/mi (feet per mile). This area coincides with a physiographic unit boundary between the Sandy Flatlands and the Everglades (fig. 3). It also generally coincides with a decrease in transmissivity of the gray limestone aquifer from west to east (fig. 28). The area with the lowest gradient occurs in the water-conservation areas of western Broward and northwestern Miami-Dade Counties (fig. 3) where the gradient is as low as 0.1 ft/mi. The hydraulic head of impounded surface water in the water-conservation areas could affect water levels with the gray limestone aquifer. This effect is suggested by the increase in gradient to as much as 0.3 ft/mi south of the water-conservation areas in Miami-Dade County (fig 31; south of Tamiami Canal).

Water-level data measured in the gray limestone aquifer were reviewed to determine if the postulated fault in northeastern Collier County (fig. 15) had any effect. No change in hydraulic head is apparent across the mapped position of the fault as shown by potentiometric-surface contours (fig. 31). However, some local water-level data were collected at the Noble’s Road site (fig. 1, well C-1139) through which the postulated fault is mapped and some anomalous differences in water levels were found. Water-level data were collected from wells C-1184 and C-1185 at the Noble’s Road site; the water level was simultaneously measured in well C-1173, which is about 2,500 ft south of the Noble’s Road site (table 11). These data, collected on March 25, 1999, indicated that the water level measured in well C-1185 on the downthrown side of the fault (fig. 17) was almost 1 ft higher than the water levels measured in wells C-1184 and C-1173, both on the upthrown side of the fault. Additionally, the local water-level gradient direction indicated by these three wells is to the west, whereas the regional gradient is to the south-southeast (fig. 31).



—10— POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface of the gray limestone aquifer on September 29, 1998, in feet above sea level. North American Vertical Datum of 1988. Interval is 2 feet. Dashed where approximately located

U D POSTULATED FAULT—D is downthrown side and U is upthrown side (from figure 15)

• 7.3 / MO-182 WELL LOCATION AND WATER LEVEL—Upper number is altitude of water level on September 29, 1998, in feet above sea level, North American Vertical Datum of 1988. Lower number is U.S. Geological Survey local well number of well measured. Asterisk after number indicates wells where water level was measured on October 3, 1998. Double asterisk indicates wells where water level was determined using an average of the water-level values for the end of September 1986-95

▲ 15.2 / MW-50 WELL LOCATION AND WATER LEVEL—Upper number is altitude of water level on September 29, 1998, in feet above sea level, North American Vertical Datum of 1988. Lower number is well number. Monitoring wells operated by the Seminole Big Cypress Indian Reservation

Figure 31. Configuration of the potentiometric surface of the gray limestone aquifer on September 29,1998. Water-level data used are given in table 11.

Table 11. Ground- and surface-water-level data collected during this study

[Well locations shown in figure 31 or figure 1 directly, or indirectly with reference to tables 1 and 2. NAVD of 88, North American Vertical Datum of 1988. Surface-water-level measurements at a site were made at about the same time as the ground-water-level measurements. Aquifer designations: GL, gray limestone or lower Tamiami; SS, sandstone; WT, water table. Other abbreviations: USGS, U.S. Geological Survey; ND, not determined; NM, not measured]

Site No.	Local number	Altitude of measurement point NAVD of 88 (feet)	Date of collection	Time of collection (hour and minutes)	Depth to water (feet)	Altitude of water level NAVD of 88 (feet)	Differential of gray limestone aquifer level above (+) or below (-) water-table aquifer level	Aquifer open in well	Depth of open interval (feet)
1	C-131	28.34	09-29-98	12:35	4.94	23.40		GL	22-54
	C-1074	28.63	09-29-98	12:30	4.23	24.40		SS	100-130
2	C-296	16.81	09-29-98	11:00	5.94	10.87		GL	8-45
3	C-495	8.69	09-29-98	9:45	3.60	5.09		GL	8-70
4	C-966	26.64	09-29-98	12:00	8.10	18.14		GL	30-40
5	C-986	19.05	09-29-98	11:30	5.33	13.72		GL	28-40
6	C-995	5.83	09-29-98	10:15	2.19	3.64		GL	28-37
7	C-1071	21.65	09-29-98	11:45	5.32	16.33		GL	20-35
8	C-1076	32.77	09-29-98	14:00	5.07	27.70		Unknown	65-85
	C-1075	32.10	09-29-98	14:10	3.04	29.06		WT	8-28
9	C-1142	19.09	09-29-98	8:58	4.73	14.36		GL	60-100
10	C-1145	12.09	09-29-98	10:21	5.18	6.91		GL	10-32
11	C-1148	12.09	09-29-98	9:45	4.28	7.81	0.01	GL	40-70
	C-1149	12.09	09-29-98	9:38	4.29	7.80		WT	9-29
12	C-1150	6.50	09-29-98	10:37	1.11	5.39		GL	25-45
13	C-1165	15.28	09-29-98	11:43	1.52	13.76		GL	24-58
14	C-1169	16.90	09-29-98	8:5	4.07	12.83		GL	77-137
15	C-1173	14.48	09-29-98	11:00	1.09	13.39	.77	GL	65-115
	C-1174	14.54	09-29-98	10:59	1.93	12.61		WT	15-25
	C-1173	14.48	03-25-99	9:25	3.05	11.43	.63	GL	65-115
	C-1174	14.54	03-25-99	9:27	3.75	10.79		WT	15-25
16	C-1179	15.98	09-29-98	9:11	0.88	15.10		GL	58-83
17	C-1181	15.26	09-29-98	8:42	1.68	13.58		GL	61-91
18	C-1182	14.25	09-29-98	11:14	2.02	12.23		GL	75-125
19	C-1183	17.30	09-29-98	9:56	2.47	14.83		GL	41-71
20	C-1184	16.40	03-25-99	9:44	4.98	11.42		GL	75-115
	C-1185	16.32	03-25-99	9:48	3.99	12.33		GL	115-145
21	G-2338	19.30	09-29-98	11:45	8.71	10.59		GL	151-161
22	G-2907	17.14	09-29-98	12:15	6.56	10.58	-0.02	GL	91-101
	G-2908	17.19	09-29-98	12:16	6.59	10.60		WT	4-14
	S-140 pumping station, tail water side					10.60		Surface water	
23	G-2909	16.20	09-29-98	10:36	4.67	11.53	.19	GL	90-100
	G-2910	16.51	09-29-98	10:33	5.17	11.34		WT	10-20
	S-8 pumping station					[1]11.00		Surface water	
	Wells are on head water side of S-8 but close to tail water side								
24	G-2911	17.16	09-29-98	12:38	7.24	9.92		GL	100-115

Table 11. Ground- and surface-water-level data collected during this study (Continued)

[Well locations shown in figure 31 or figure 1 directly, or indirectly with reference to tables 1 and 2. NAVD of 88, North American Vertical Datum of 1988. Surface-water-level measurements at a site were made at about the same time as the ground-water-level measurements. Aquifer designations: GL, gray limestone or lower Tamiami; SS, sandstone; WT, water table. Other abbreviations: USGS, U.S. Geological Survey; ND, not determined; NM, not measured]

Site No.	Local number	Altitude of measurement point NAVD of 88 (feet)	Date of collection	Time of collection (hour and minutes)	Depth to water (feet)	Altitude of water level NAVD of 88 (feet)	Differential of gray limestone aquifer level above (+) or below (-) water-table aquifer level	Aquifer open in well	Depth of open interval (feet)
25	G-3295C	8.64	09-29-98	9:04	0.29	8.35	.21	GL	127-130
	G-3295A	8.53	09-29-98	9:00	.39	8.14		WT	17-20
26	G-3296C	11.49	09-29-98	11:26	3.16	8.33	.09	GL	144-144
	G-3296A	10.33	09-29-98	11:28	2.09	8.24		WT	20-20
27	G-3302C	10.81	09-29-98	8:30	2.80	8.01	-.24	GL	120-123
	G-3302A	10.54	09-29-98	8:27	2.29	8.25		WT	14-14
	S-333, west side of structure					8.60			
28	G-3303C	9.31	09-29-98	10:56	2.75	6.56	.18	GL	127-130
	G-3303A	9.51	09-29-98	10:51	3.13	6.38		WT	20-20
	S-333, east side of structure					6.00		Surface water	
29	G-3309C	6.41	09-29-98	10:07	.37	6.04	-.63	GL	127-130
	G-3309A	6.99	09-29-98	10:05	.32	6.67		WT	20-20
	L-67 Extension (canal on west side of levee)					6.52		Surface water	
30	G-3310C	5.73	10-03-98	9:36	.02	5.71	-.04	GL	130-133
	G-3310A	5.86	09-29-98	12:07	.12	5.74		WT	19-19
31	G-3311D	6.69	09-29-98	13:07	2.07	4.62	.50	GL	157-160
	G-3311A	6.87	09-29-98	13:04	2.75	4.12		WT	20-23
32	G-3314C	5.11	09-29-98	10:47	1.64	3.47	.21	GL	187-190
	G-3314A	5.08	09-29-98	10:45	1.81	3.27		WT	27-30
33	G-3317C	ND	09-29-98	9:53	.71	Unknown		GL	147-150
	G-3317D	ND	09-29-98	9:49	.57	Unknown		WT	8-28
34	G-3318C	5.22	09-29-98	8:54	1.79	3.43	-0.19	GL	158-161
	G-3318A	5.47	09-29-98	8:51	1.85	3.62		WT	23-23
35	G-3394B	4.27	10-03-98	13:15	0.06	4.21		GL	110-145
36[2]	HE-855	28.80	09-29-98	9:51	2.88	25.92	-.51	GL	70-90
	HE-856	28.32	09-29-98	9:50	1.89	26.43		WT	6-11
37	HE-859	27.75		See footnote 3		22.70		GL	58-59
38[2]	HE-861	16.54	NM					GL	37-70
	HE-862	15.71	09-29-98	11:33	4.58	11.13		WT	7-10
39	HE-868	20.71		See footnote 3		19.60		GL	84-97
40[2]	HE-884	19.48	09-29-98	11:51	4.24	15.24		GL	62-67
41[2]	HE-1037	26.21	09-29-98	9:20	1.98	24.23	-.48	GL	70-120
	HE-1036	25.34	09-29-98	9:19	.63	24.71		WT	5-10
42[2]	HE-1042	21.77	09-29-98	10:29	1.17	20.60		GL	40-80
43[2]	HE-1063	17.04	09-29-98	11:57	.08	16.96	.00	GL	78-123
	HE-1062	16.96	09-29-98	11:56	.00	16.96		WT	5-10
44[2]	HE-1075	14.76	09-29-98	12:45	4.88	9.88		GL	135-155

Table 11. Ground- and surface-water-level data collected during this study (Continued)

[Well locations shown in figure 31 or figure 1 directly, or indirectly with reference to tables 1 and 2. NAVD of 88, North American Vertical Datum of 1988. Surface-water-level measurements at a site were made at about the same time as the ground-water-level measurements. Aquifer designations: GL, gray limestone or lower Tamiami; SS, sandstone; WT, water table. Other abbreviations: USGS, U.S. Geological Survey; ND, not determined; NM, not measured]

Site No.	Local number	Altitude of measurement point NAVD of 88 (feet)	Date of collection	Time of collection (hour and minutes)	Depth to water (feet)	Altitude of water level NAVD of 88 (feet)	Differential of gray limestone aquifer level above (+) or below (-) water-table aquifer level	Aquifer open in well	Depth of open interval (feet)
45	HE-1111	14.51	09-29-98	11:48	3.85	10.66		GL	38-118
	HE-1110	ND	09-29-98	11:42	3.05			GL	[4]146-156
	L-3 canal					14.30		Surface water	
46	MO-182	11.21	09-29-98	9:05	3.90	7.31	.12	GL	93-118
	MO-183	8.75	09-29-98	9:10	1.56	7.19		WT	13-23
	MO-187	10.95	09-29-98	9:13	3.64	7.31		GL	70-80
47	MO-184	8.93	09-29-98	14:24	3.15	5.78		GL	30-80
48	PB-1703	16.84	09-29-98	9:43	7.55	9.29		GL	75-85
	G-200 pumping station					8.90[1]		Surface water	
49	PB-1704	10.96	09-29-98	8:42	3.95	7.01		GL	82-112
50	PB-1705	15.25	09-29-98	8:06	5.86	9.39	-.13	GL	86-96
	PB-1706	15.25	09-29-98	8:12	5.73	9.52		WT	6-16
	S-7 pumping station, head water side					9.8-10.1		Surface water	
[5]51	OBS1N	[6]12.85	09-30-99	14:30	1.44	11.4	2.2	GL	65-140
	WTIN	[6]12.5	09-30-98	14:57	3.24	9.3		WT	5-8
[7]52	MW-2		09-29-98	8:00		12.40	-0.40	GL	63-120
	MW-4		09-29-98	10:00		12.80		WT	10-20
[7]53	MW-3		09-29-98	12:00		13.40		GL	78-100
[7]54	MW-3D		09-29-98	10:00		16.00	-1.30	GL	70-100
	MW-3S		09-29-98	6:00		17.30		WT	20-30
[7]55	MW-5		09-29-98	9:00		12.10		GL	70-100
[7]56	MW-35		09-29-98	9:00		14.20		GL	63-102
[7]57	MW-50		09-29-98	10:00		15.20		GL	63.5-105
[7]58	DW-W		09-29-98	10:00		17.00		GL	78-120.6

[1]Average of head water and tail water.
[2]Water-level data collected by South Florida Water Management District.
[3]Altitude of water level is average of end of September values from historical data for the 1986-95 period.
[4]Depth of bentonite seal above screen in well not known.
[5]Site 51 is on the Miccosukee Indian Reservation at the north aquifer test site (Murray-Milleson, 1989). Site locations is shown in figure 23 (map no. 16).
[6]Estimated using topographic map and measurement of top of casing height above ground surface, accurate to only 1 or 2 feet.
[7]Sites 52 to 58 are on the Seminole Big Cypress Indian Reservation. The water-level altitudes were read from continuous chart records. Site locations are shown in figure 31, except for site 58 which is at site 43.

Water Quality

Field-measured specific conductance data were collected to help delineate the water-quality variations within the gray limestone aquifer and to gain an understanding of the ground-water flow patterns. A plot of the relation between field-derived specific conductance and chloride concentration for water samples collected from 60 wells completed in the gray limestone aquifer was constructed by using data given in table 12 (fig. 32). A least-squares linear relation with a coefficient of determination of 0.88 was obtained; using this relation, a specific conductance of about 1,500 μS/cm (microsiemens per centimeter) approximately equals a chloride concentration of 250 mg/L. Water that is dominated by chloride ions has been shown to have a specific conductance/chloride concentration ratio of about 3:1 (Schiner and others, 1988), whereas water from the gray limestone aquifer has a ratio of 4:1 or higher (fig. 32). The higher ratio for gray limestone aquifer water is due to increased mineralization of the water, probably because of long residence time of the water in the aquifer. Water from the gray limestone aquifer contains calcium, sodium, bicarbonate, potassium, magnesium, and sulfate ions at a milliequivalent ratio to chloride higher than that found in seawater (Howie, 1987, fig. 6, Stiff diagrams). The samples with higher chloride concentration–greater than 200 or 250 mg/L–indicate the presence of connate water.

Table 12. Selected water-quality data from the gray limestone and sand aquifers

[Well locations shown in figure 33 or figure 1 directly, or indirectly with reference to tables 1 and 2. mg/L, milligrams per liter; μS/cm, microsiemens per centimeter; --, not available or not measured; ?, depth of casing unknown]

USGS local well number	Sampling date	Chloride concentration (mg/L)	Specific conductance field (μS/cm)	Specific conductance lab (μS/cm)	Depth of open interval in completed well (feet below land surface)		Depth of drilling sample (feet below land surface)	Depth of gray limestone aquifer (feet below land surface)	
					Top	Bottom		Top	Bottom
Gray Limestone Aquifer									
C-131[1]	10-27-86	80	878	--	22	54		20	80
C-296	10-19-92	160	1,740	--	8	45		[2]5	[2]55
C-495	10-19-92	16	370	--	8	70		[2]5	[2]90
C-966	10-21-92	18	530	--	30	40		[2]5	[2]55
C-986	10-19-92	46	620	--	28	40		[2]10	[2]115
C-1071	10-21-92	40	582	--	20	35		[2]10	[2]90
C-1142[3]	09-02-98	150	1,900	1,760	60	100		58	100
C-1145[3]	08-27-98	12	526	456	10	32		18	53
C-1148[3]	08-28-98	20	697	678	40	70		25	82
C-1150[3]	08-28-98	16	574	554	25	45		2	53
C-1165[3]	08-28-98	61	931	967	24	58		21	71
C-1169[3]	08-31-98	120	1,170	1,130	77	137		75	139
C-1173[3]	09-02-98	150	1,900	1,750	65	115		65	115
C-1179[3]	09-02-98	67	1,060	994	53	83		55	144
C-1181[3]	08-31-98	170	1,100	1,090	61	91		42	99
C-1182[3]	08-31-98	240	1,550	1,510	75	125		74	122
C-1183[3]	09-01-98	120	1,150	1,110	41	71		41	83
C-1184	01-18-99	200	1,323	1,670	75	115		73	118
C-1185	01-06-99	195	1,437	1,520	115	145		91	146
C-1185	01-18-99	--	1,485	--	115	145		91	146
G-2311[4]	05-27-81	870	3,560	--			149	138	163
G-2312[4]	05-28-81	165	1,230	--			159	105	170

Table 12. Selected water-quality data from the gray limestone and sand aquifers (Continued)

[Well locations shown in figure 33 or figure 1 directly, or indirectly with reference to tables 1 and 2. mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; --, not available or not measured; ?, depth of casing unknown]

USGS local well number	Sampling date	Chloride concentration (mg/L)	Specific conductance field (µS/cm)	Specific conductance lab (µS/cm)	Depth of open interval in completed well (feet below land surface)		Depth of drilling sample (feet below land surface)	Depth of gray limestone aquifer (feet below land surface)	
					Top	Bottom		Top	Bottom
G-2313[4]	06-01-81	360	2,100	--			119	42	155
G-2314[4]	06-02-81	200	1,700	--			129	40	155
G-2315[4]	06-04-81	1,250	4,330	--			159	116	192
G-2316[4]	06-05-81	118	1,095	--			149	93	158
G-2319[4]	06-12-81	550	2,750	--			149	113	166
G-2320[4]	06-16-81	345	2,000	--			129	85	168
G-2321[4]	06-18-81	125	1,100	--			159	149	161
G-2329[4]	07-10-81	145	1,240	--			129	73	137
G-2330[4]	07-14-81	327	2,050	--			129	63	167
G-2338[4]	07-15-81	200	1,600	--			149	97	154
G-2340[4]	07-16-81	230	1,575	--			119	60	147
G-2346[4]	08-05-81	245	1,650	--			120	57	128
G-2907[3]	09-03-98	160	1,320	1,270	90.6	101		[2]60	[2]180
G-2909[1]	08-25-94	803	3,510	3,410	90	100		[2]40	[2]135
G-2911[1]	10-04-96	260	[5]1,560	--	100	115		[2]85	[2]175
G-3294C	06-08-84	300	1,360	1,470	147	150		138	179
G-3295C	09-09-98	45	908	876	127	130		57	135
G-3296C	09-09-98	60	1,003	943		[6]144		70	174
G-3297[4]	09-14-83	205	1,210	--			140	121	147
G-3298[4]	09-21-83	46	620	--			170	140	166
G-3301[4]	05-25-83	40	640	--			150	72	152
G-3301C	06-01-64	35	797	--	?	130		72	152
G-3302C	09-09-98	63	920	776	120	123		79	138
G-3303C	09-09-98	150	982	959	127	130		91	160
G-3304C	04-06-84	42	646	--	127	130		119	144
G-3305C	07-16-84	51	686	--	117	120		105	132
G-3308C	06-06-84	39	585	--	127	130		111	160
G-3309C	09-09-98	35	855	850	127	130		100	138
G-3310C	09-09-98	15	370	373	130	133		153	182
G-3311D	09-09-98	19	485	477	157	160		135	174
G-3314C	09-09-98	16	391	386	187	190		181	210
G-3317C	11-14-84	2,000	4,020	--	147	150		84	153
G-3318C	09-09-98	830	2,980	2,780	158	161		132	166
HE-855	10-20-92	82	760	--	70	90		[2]40	[2]90
HE-859	10-20-92	58	791	--	70	90		[2]45	[2]130
HE-861	10-20-92	48	562	--	37	70		[2]45	[2]185
HE-868[1]	10-31-86	135	1,043	--	84	97		95	[2]140
HE-1021[1]	10-06-86	158	1,253	--	Unknown (lower Tamiami aquifer)			40	140

Table 12. Selected water-quality data from the gray limestone and sand aquifers (Continued)

[Well locations shown in figure 33 or figure 1 directly, or indirectly with reference to tables 1 and 2. mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; --, not available or not measured; ?, depth of casing unknown]

USGS local well number	Sampling date	Chloride concentration (mg/L)	Specific conductance field (µS/cm)	Specific conductance lab (µS/cm)	Depth of open interval in completed well (feet below land surface)		Depth of drilling sample (feet below land surface)	Depth of gray limestone aquifer (feet below land surface)	
					Top	Bottom		Top	Bottom
HE-1037	10-20-92	94	980	--	70	120		75	120
HE-1042	10-21-92	125	1,270	--	40	80		40	75
HE-1054	10-29-87	98	1,100	--	30	100		55	140
HE-1063	10-20-92	164	1,276	--	78	123		78	124
HE-1075	10-19-92	580	2,990	--	135	155		62	156
HE-1111[3]	08-29-98	54	620	605	38	118		35	148
HE-1112	01-05-99	40	808	813	50	80		46	80
HE-1113	12-30-98	26	742	785	35	50		35	50
HE-1114	12-30-98	32	694	732	67	82		65	85
HE-1115	03-10-99	215	1,445	1,660	105	120		105	125
HE-1116	03-26-99	200	1,320	1,530	140	150		47	152
HE-1117	03-26-99	80	831	960	50	80		47	152
MO-180	06-18-97	160	1,222	--	95	120		48	126
MO-184[3]	08-28-98	19	605	541	30	80		0	85
MO-187	01-13-98	55	840	841	70	80		48	126
MO-188	03-02-98	--	1,800	--	89	114		48	126
MO-188[3]	08-27-98	200	1,290	1,260	89	114		48	126
PB-840	12-19-74	1,100	4,300	--	84	260		[2]60	[2]160
PB-1428[4]	07-01-81	1,700	6,250	--			159	135	162
PB-1703[3]	08-29-98	66	795	780	75	85		80	92
PB-1704[3]	08-29-98	270	2,680	2,800	82	112		73	172
PB-1705[3]	09-03-98	150	1,280	1,220	86	96		[2]110	[2]170
Sand Aquifer or Deeper									
C-1141[3]	08-28-98	840	3,520	3,540	88	108		Sand aquifer	
C-1143[3]	08-28-98	57	1,020	1,010	180	200		Sand aquifer	
C-1144[3]	08-27-98	41	777	757	120	130		Sand aquifer	
C-1164[3]	09-02-98	95	979	915	48	253		Sand aquifer	
C-1177[3]	08-28-98	219	987	1,990	143	168		Sand aquifer	
MO-178[3]	08-27-98	30	825	745	412	452		Arcadia Formation	

[1]Non-U.S. Geological Survey sample.

[2]Contact estimated from contour map to the nearest 5 feet.

[3]Analysis also included color, dissolved-solids concentration, pH, total alkalinity, all major ions, and low-level nutrient analysis (all phosphorous and nitrogen species). This additional data is archived in the USGS water-quality data storage and retrieval database (QWDATA).

[4]Sampled collected while drilling with reverse-air rotary method.

[5]Specific conductance calculated from chloride concentration value using relationship shown in figure 32.

[6]Cased to total depth.

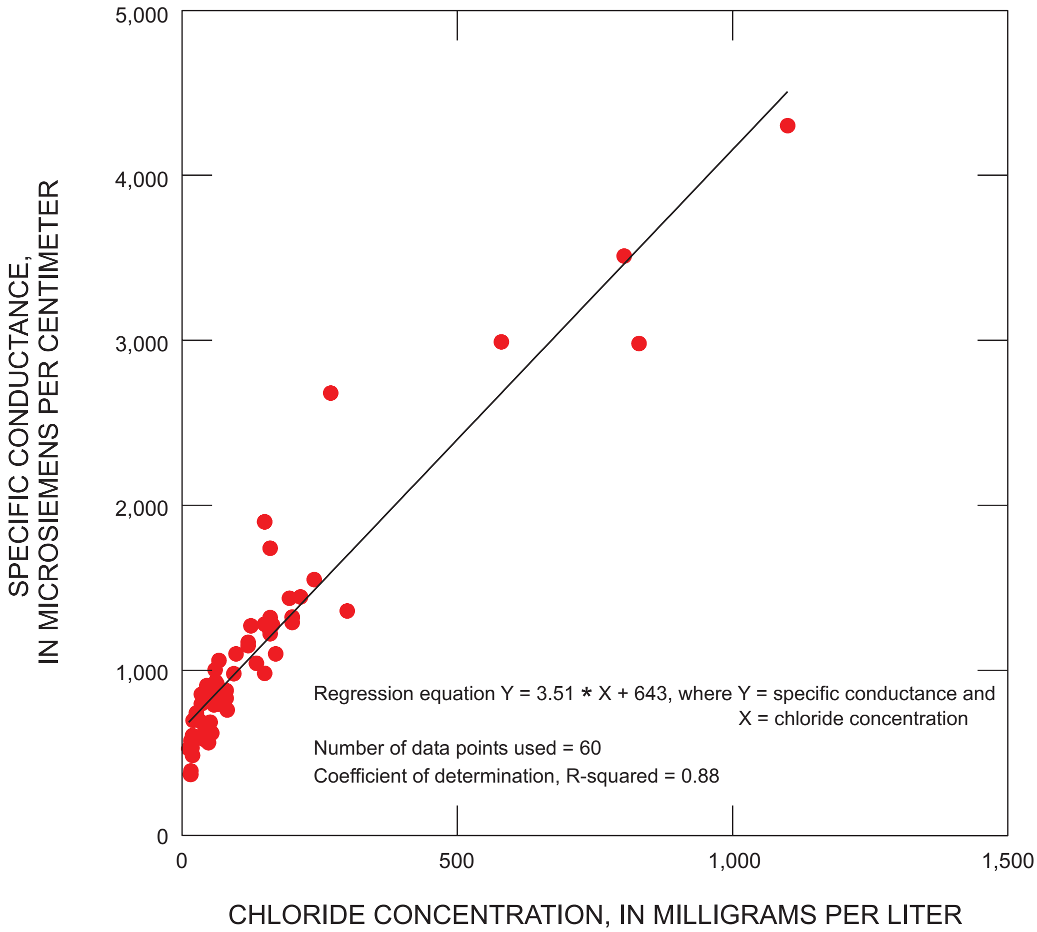


Figure 32. Relation between chloride concentration and field specific conductance for water samples collected from wells completed in the gray limestone aquifer.

In a study of the chemical characteristics of water in the surficial aquifer system in Broward County, samples were collected at 10-ft intervals while drilling with the dual-tube reverse-air method; results indicated that specific conductance in the gray limestone aquifer usually increases with depth (Howie, 1987). Based on these data, the increase in specific conductance with depth in the aquifer was sometimes abrupt, such as in wells G-2313 and G-2314 located along the Broward/Palm Beach County line in northwestern Broward County. For example, in well G-2313, specific conductance increased from 640 to 5,800 µS/cm with depth in the aquifer, which extends from 42 to 155 ft below land surface. The increase was not gradual but occurred abruptly at the depths of about 110 and 130 ft where specific conductance nearly doubled.

The sudden increases in specific conductance with depth that occur in the gray limestone aquifer probably are related to the presence of semiconfining layers contained within the aquifer. These units probably retard downward seepage of recharged meteoric water and the dilution of connate water in the lower part of the aquifer. For example, at the Trail Center site (fig. 1, well MO-178) where the aquifer is interpreted to occur at depths of between 48 and 126 below land surface (fig. 24), poorly permeable limestone containing a carbonate mud-rich matrix occurs at depths of between 80 and 96 ft below land surface and serves to divide the aquifer into upper and lower permeable intervals. Wells MO-187 and MO-188 at this site have screened intervals at depths from 70 to 80 ft and 89 to 114 ft below land surface, respectively, which are effectively above and below this poorly permeable layer (fig. 26). Samples collected from these wells showed that specific conductance from the shallow well was less than half that in the deep well (table 12).

Water from wells MO-187 and MO-188 had specific conductances of 840 and 1,800 µS/cm, respectively.

Although these semiconfining units within the aquifer serve to stratify water, they do not necessarily cause differences in head within the aquifer during natural or stressed hydrologic conditions. At the Trail Center site, water levels in wells MO-187 (70 to 80 ft below land surface) and MO-182 (93 to 118 ft below land surface) were identical on September 29, 1998. Analysis of drawdown data from the gray limestone aquifer test at the Trail Center site gave approximately the same transmissivity estimates for monitoring wells completed in the upper and lower permeable intervals, even though the production well (89 to 114 ft below land surface) was open only in the lower interval (fig. 26).

The distribution of specific conductance within the gray limestone aquifer principally during the wet season (June through October) was mapped (fig. 33) by using field-measured specific conductance data reported from 73 wells (table 12). A total of 63 of the samples used were collected during the wet season, of which 25 were from August 27 to September 9, 1998; however, dry-season specific conductance values were used for 10 wells due to a lack of available wet-season data. Data from 17 wells were collected while drilling with the dual-tube, reverse-air method (fig. 33); monitoring wells were not completed in the gray limestone aquifer at these sites. For these 17 wells, an attempt was made to choose a sample taken at a depth that was representative of the whole aquifer. Because of the compartmentalization of the aquifer as discussed above, this was difficult in some cases.

Several wells completed in the gray limestone aquifer were sampled both during the dry season and wet season, and, in most cases, the change in water quality was not great. For example, well C-1165 at the Bear Island Campground site (fig. 33) was sampled during both periods, and specific conductance decreased from 1,020 µs/cm on January 28, 1998, to 931 µs/cm on August 28, 1998.

Specific conductance of water from the gray limestone aquifer in the study area varies widely, but is generally less than 1,500 µS/cm in most areas (fig. 33). High specific conductance (from 3,000 to 6,300 µS/cm) occurs in Palm Beach County; parts of central and northern Broward County; and southwestern Miami-Dade County. Low specific conductance (less than 500 µS/cm) is found in south-central and eastern Miami-Dade County and a small area within western Collier County. Some of the local variations may be the result of samples collected at different depths within the aquifer in nearby wells. For example, in Palm Beach County, well PB-1704 was screened over a 30-ft interval within the upper part of a 100-ft thick aquifer, whereas the entire aquifer is open in well PB-840 located about 5 mi to the northwest of well PB-1704. The specific conductance values are 2,700 and 4,300 µS/cm for wells PB-1704 and PB-840, respectively (fig. 33). A semiconfining layer of low to very low hydraulic conductivity was penetrated in well PB-1704 at a depth of 110 ft below land surface within the aquifer (appendix II), which is about the depth of the bottom of the screened interval.

Areas of high specific conductance in the gray limestone aquifer are probably caused by confining units, both above and within the aquifer, or a low potentiometric surface gradient in the aquifer that causes ground-water movement from distant recharge areas to be slow. The areas of high specific conductance in Palm Beach County and parts of northern Broward County could result from both of these factors. The easterly directed head gradient in these areas is very low (fig. 31). The area of high specific conductance in central to south-central Broward County, defined by samples from wells G-2319 and G-2311 (fig. 33), also coincides with an area where the upper confining unit thickness exceeds 50 ft (fig. 29). An area of higher specific conductance (greater than 1,500 µS/cm) that extends from southern Hendry County to the southeast through eastern Collier County and into southwestern Broward County could also be attributed to confinement above the aquifer. The upper confining unit is greater than 50 ft thick in much of this area.

The areas of high specific conductance in Palm Beach County and parts of northern Broward County (fig. 33) could be the result of seawater invasion during the Pleistocene, followed by incomplete flushing of the aquifer (Parker and others, 1955, p. 821). An area of high chloride concentration (more than 500 mg/L) was mapped in roughly the same area as these areas of high specific conductance for a depth interval from 51 to 100 feet (Parker and others, 1955; fig. 221C).

An area of low specific conductance (less than 1,500 µS/cm) extends from southern Hendry County through well HE-861 to the southeast into western Broward County (fig. 33). Much of this area has good confinement on the basis of the thickness of the upper confining unit and on leakance values estimated from aquifer tests (fig. 29). This area of low specific conductance probably is caused by the movement of fresh ground water to the southeast that has its source as

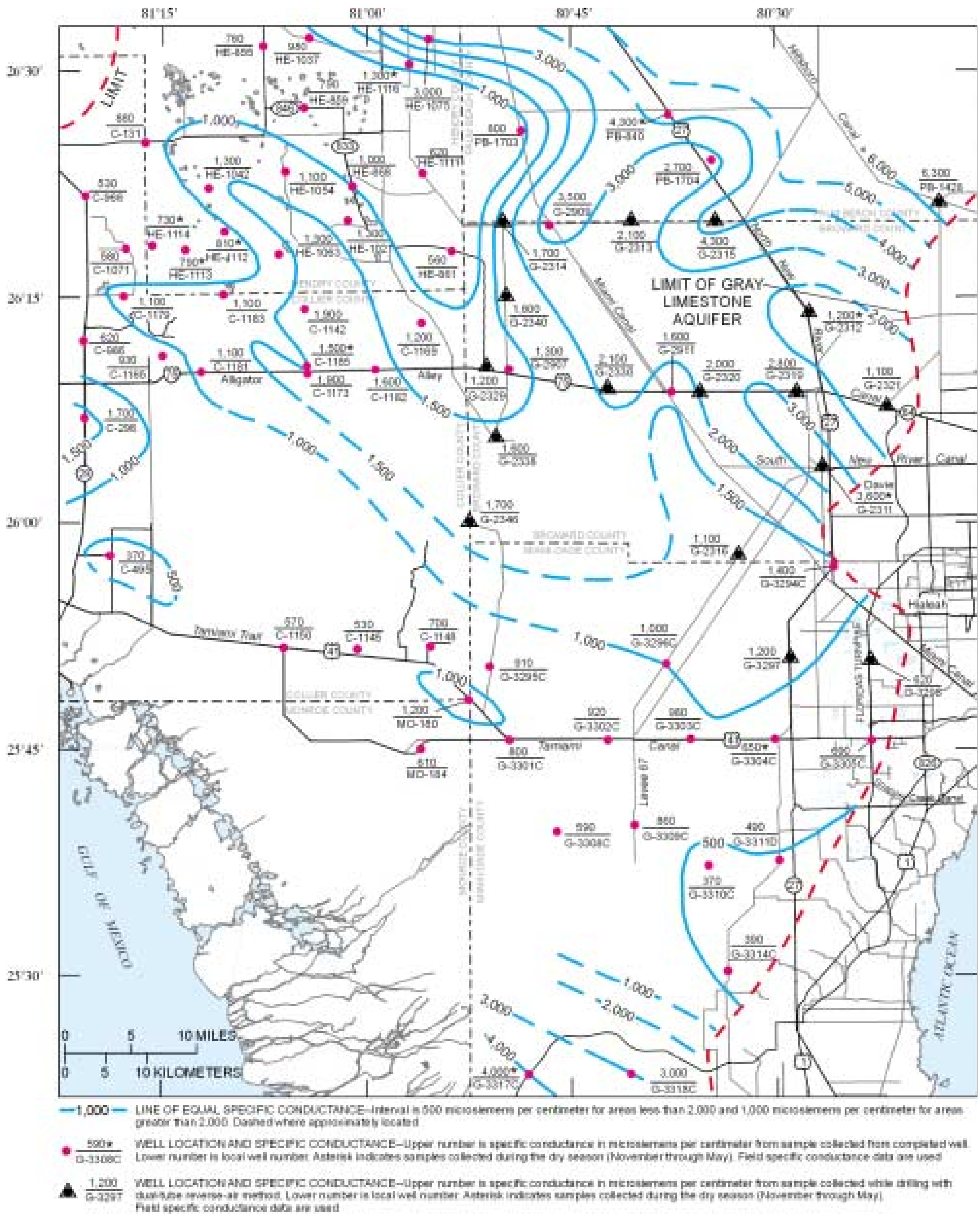


Figure 33. Distribution of specific conductance of water in the gray limestone aquifer during the wet season. Limit of gray limestone aquifer is indicated by red dashed line.

recharged meteoric water in Hendry County. Ground-water flow, as indicated by the potentiometric surface (fig. 31), is directed to the southeast in much of this area of low specific conductance. Additionally, an area of high transmissivity (greater than 50,000 ft^2/d) has been mapped in this area, and it also extends to the southeast (fig. 28). Hydraulic conductivity is likely to be higher in a direction parallel to this area of high transmissivity, and ground-water flow would tend to be directed along this area as it moves downgradient.

SUMMARY AND CONCLUSIONS

The gray limestone aquifer of the surficial aquifer system is a potential supplemental source for public-water supply in central-south Florida. Prior to this study, the relations between the wetlands and shallow aquifers were not well defined, and additional hydrologic data were needed to improve characterization of the hydraulic properties of the aquifers of the surficial aquifer system. Stratigraphic and hydrogeologic correlation between the east and west coastal areas in the surficial aquifer system was needed.

To address these needs, 35 test wells were drilled, of which 33 were continuously cored. All collected cores samples were described, selected intervals were analyzed for porosity and permeability, and thin sections of selected samples were examined. Extensive borehole geophysical logging was done in many of the test wells. Wells were installed at most test corehole sites, and aquifer testing of the gray limestone aquifer was conducted at six sites that included four multiwell tests and six single-well tests. Water-quality data were collected from all wells installed, and synoptic water levels of the gray limestone and water-table aquifers were determined in 69 wells at 47 sites.

The lithologic units of primary interest to this study include the Peace River Formation of the Hawthorn Group, the unnamed formation, Tamiami Formation (Ochopee Limestone and Pinecrest Sand Member), and younger rock and sediment of Pleistocene age. The unnamed formation consists of relatively clay-free quartz sands and sandstones overlying clay-rich siliciclastics of the Peace River Formation and underlying the lowest limestones of the Ochopee Limestone.

The Ochopee Limestone consists of mixed siliciclastic-carbonate rocks that contain a heterozoan carbonate-particle association. The heterozoan carbonate particles accumulated in a carbonate ramp depositional system. The extensive carbonate ramp sequence that forms the Ochopee Limestone could have been deposited during transgressive to high-stand conditions in the early Pliocene; the bounding marine siliciclastic shelf deposits (unnamed formation and Pinecrest Sand) were deposited during low-stand conditions. Subtle regional-scale facies patterns that characterize ramp depositional systems suggest that gross hydraulic properties of the gray limestone aquifer are predictable.

The gray limestone aquifer of the surficial aquifer system includes moderately to highly permeable limestones, sandstones, and sand of the Ochopee Limestone. Additionally, quartz sands and sandstones of the uppermost part of the unnamed formation were included as part of the gray limestone aquifer if hydraulic conductivity was high to very high, or if they contained moldic porosity. The Ochopee Limestone part of the aquifer is primarily composed of pelecypod lime rudstones and floatstones with common skeletal-moldic pore spaces. The aquifer overlies less-permeable quartz sand and sandstone of the unnamed formation and Peace River Formation. In most areas, the aquifer is overlain by a confining to semiconfining unit, and this unit usually consists of poorly permeable clayey quartz sands and terrigenous mudstones of the Pinecrest Sand.

In general, the gray limestone aquifer thickens where the base of the aquifer is structurally low and, based on a previous study, where the top of a deeper formation also is low. This coincidence suggests that the thickest deposition of the gray limestone aquifer occurred in paleotopographic low areas, or that structural movements during deposition influenced the thickness of the gray limestone aquifer. A northwest-southeast trending fault is postulated to be present in eastern Collier County based on structure at the base of the gray limestone aquifer. Vertical offset at the base of the aquifer caused by this fault could be as great as 60 ft. Local thickening of correlative units across the fault to its downthrown side, found to occur at one of the test corehole sites, is consistent with movement along this inferred fault during deposition of the Ochopee Limestone and possibly the Pinecrest Sand.

The gray limestone aquifer extends over most of the study area except in a small area in northwestern Collier County. The gray limestone aquifer is the same as the lower Tamiami aquifer in southern Hendry County; to the west and south in Collier and Monroe Counties, it becomes the water-table aquifer and the upper part of the lower Tamiami aquifer. The thickness of the gray limestone aquifer ranges from 30 to 100 ft over most of the study area. The eastern limit of the gray limestone aquifer occurs where permeable facies that constitute the aquifer grade eastward into less permeable facies, or where the aquifer merges with the Biscayne aquifer and the intervening semiconfining unit wedges out. South of Tamiami Trail in Miami-Dade County, the eastern limit of the aquifer corresponds to the limits of the Ochopee Limestone carbonate ramp where these rocks are transitional with less-permeable siliciclastics of the Pinecrest Sand and the unnamed formation.

The rock-pore types within the gray limestone aquifer are mainly intergranular and separate vug (skeletal-moldic) pore spaces. Solution-enlarged pore spaces and minor intragrain, root-mold and boring porosity are distributed locally. Aquifer tests and semi-quantitative and quantitative core analyses of gray limestone aquifer core samples indicate that the rock-fabric and associated primary and secondary pore spaces combine to form a dual diffuse-carbonate and conduit flow system capable of yielding large quantities of water.

The transmissivity of the gray limestone aquifer is reported to be as much as 90,000 ft^2/d based on historical aquifer test data for Miami-Dade and Broward Counties. Transmissivity of the equivalent lower Tamiami aquifer in Hendry County is as much as 125,000 ft^2/d. Tests conducted during this study suggest that transmissivity and hydraulic conductivity in the gray limestone aquifer are at least as high as 300,000 ft^2/d and 12,000 ft/d, respectively. Two areas of high transmissivity (greater than 50,000 ft^2/d), both of which trend northwest-southeast, were mapped. One extends through southern Hendry County and into west-central Broward County, and the other extends from central Collier County to northern Monroe County. The very high transmissivity (as much as 300,000 ft^2/d) in the area extending through eastern Collier County could be associated with the structural position of the aquifer in this area. In this area, the aquifer lies near the land surface and is unconfined to semi-confined; greater rates of meteoric recharge in this area as compared to areas where the aquifer is better confined could have enhanced dissolution in the aquifer.

Based on aquifer tests, hydraulic conductivity within the aquifer is reported to range from about 200 to 12,000 ft/d, but this property for individual flow zones probably is much larger. Flow-zone thicknesses within the gray limestone aquifer were determined from heat pulse flowmeter data; most of the flow within the aquifer occurs within relatively thin zones that are highly permeable. These flow zones are usually only 5 to 10 ft thick and are separated by intervals of low to moderate hydraulic conductivity that can act as semiconfining units. The hydraulic conductivity within the gray limestone aquifer generally increases from east to west across the study area, and this pattern is related to a shallowing of the depositional profile of the Ochopee Limestone carbonate ramp in the same direction.

The gray limestone aquifer is semiconfined or confined in most areas but is unconfined to the south and west in Collier and Monroe Counties. The thickness of the upper confining unit ranges from 20 to 60 ft in most of the area where the unit is present. The leakance of the upper confining unit is as low as about 1.0×10^{-6} 1/d based on aquifer tests. Sites with a leakance of less than 1.0×10^{-3} 1/d, a value considered to indicate good confinement, are located in areas where the thickness of the upper confining unit approaches or is more than 50 ft. Areas where the upper confining unit is 50 ft thick or greater are in southwestern Palm Beach County and parts of southern Hendry, eastern Collier, Broward, and Miami-Dade Counties.

A semiconfining unit is present below the gray limestone aquifer in most of the study area and is usually contained within the unnamed formation. This semiconfining unit is usually underlain by confining beds at the top of the Peace River Formation that mark the base of the surficial aquifer system. In some areas, the unnamed formation contains a sand aquifer, and some confinement separates this aquifer from the gray limestone aquifer based on lithology, core sample analysis, analysis of aquifer-test and flowmeter data, and changes in water quality and hydraulic head. However, some previous investigators have combined the gray limestone aquifer and the sand aquifer of the unnamed formation into one aquifer, referred to as the lower Tamiami aquifer.

Water levels in the gray limestone aquifer on September 29, 1998, ranged from as much as 26 ft above sea level (North American Vertical Datum of 1988) in central Hendry County to less than 4 ft above sea level in coastal areas. The direction of groundwater flow is to the south or southwest in part of southern Hendry County, most of Collier County, Monroe County, and western Miami-Dade County; in most of the rest of the study area, flow is to the east or southeast. Based on differences in water levels between the gray limestone aquifer and the overlying water-table aquifer, recharge is indicated for the gray limestone aquifer in central and southern Hendry County, and discharge is indicated in eastern Collier County, Broward County, and Miami-Dade County.

During the wet season (June through October), the specific conductance of water from the gray limestone aquifer ranged from less than 500 to greater than 6,000 µS/cm in the study area. However, in most areas, specific conductance was 1,500 µS/cm or less, a value that approximately equates to a dissolved chloride concentration of 250 mg/L. Areas of higher specific conductance (greater than 3,000 µS/cm) probably are caused either by confining units, both above and within the aquifer, which retard downward seepage of recharged meteoric water into the aquifer, or by a low potentiometric-surface gradient, or by both of these factors. Specific conductance tends to be high in areas where the upper confining unit is 50 ft thick or greater.

An area with a specific conductance of less than 1,500 µS/cm extends from southern Hendry County toward the southeast into western Broward County. However, much of this area is indicated to have good confinement, based on the thickness of the upper confining unit and hydraulic properties estimated from aquifer tests. An area of high transmissivity (greater than 50,000 ft^2/d) was mapped in this area and trends in the same direction. The hydraulic head gradient also is to the southeast in this area. Relatively rapid downgradient movement of ground water that has been recharged in Hendry County probably causes this area of low specific conductance.

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APPENDIXES

For your convenience, the appendixes are provided separately—

Appendix I can be accessed at:

Appendix II can be accessed at:

Appendix III can be accessed at: